Parity Violation in Deep Inelastic Scattering (PVDIS) with a Solenoidal Large Intensity Device (SoLID) at Jlab

Electroweak and Hadronic Physics

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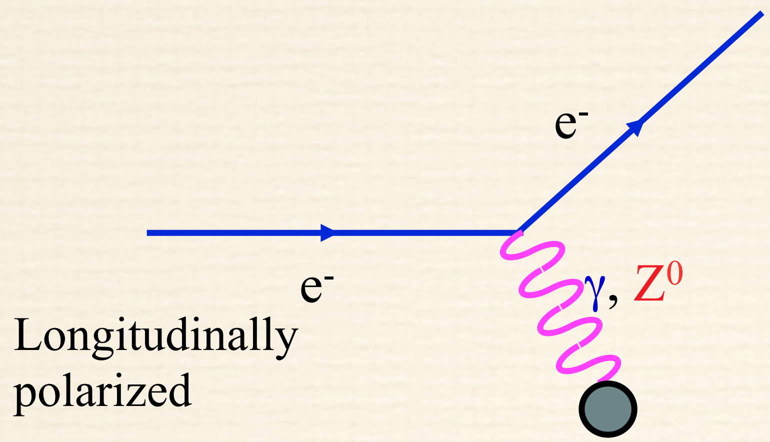
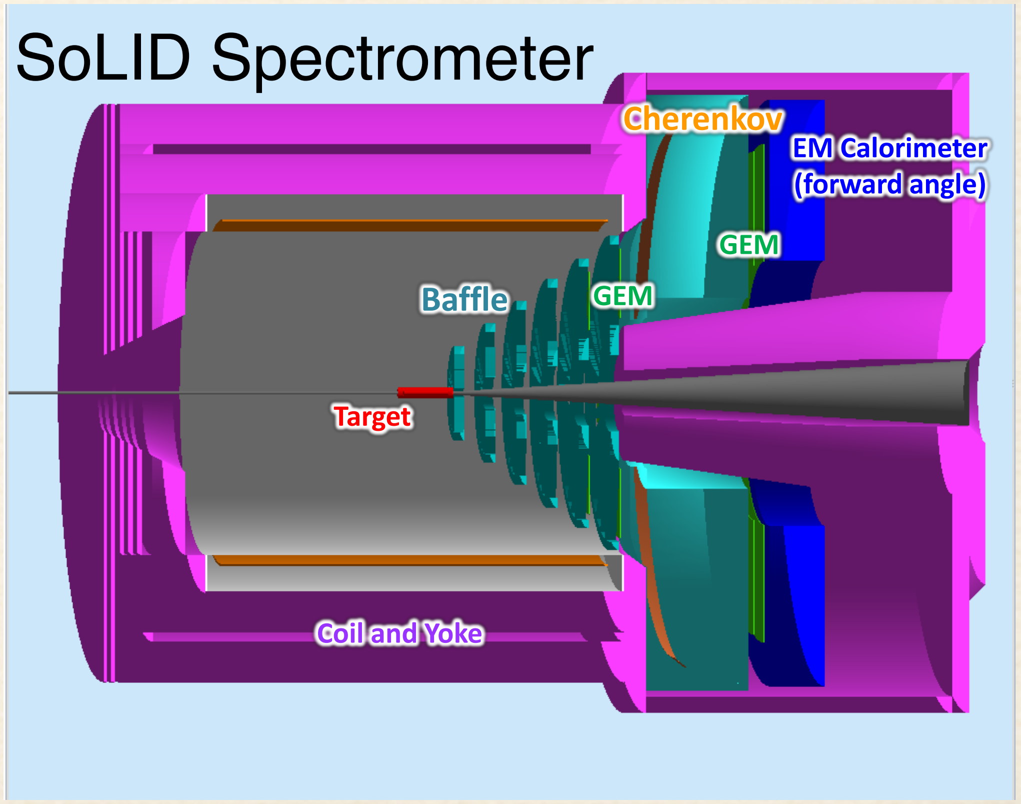
Acknowledgments: A. Deshpande, J. Erler, K. Kumar W. Marciano, K. Paschke, M. Ramsey-Musolf, X. Zheng, P. Reimer, M. Paolone, N. Liyange, R. Holmes, S Riordan, …, SoLID Collaboration

PVDIS Outline



Credit: P. Reimer

I. Searches for new physics in NP and HEP and role of PVES in general and SoLID in particular.
II. PVDIS and QCD
   A. Charge Symmetry
   B. Higher Twist
   C. Other Physics and Targets: d_v/u_v ; Isoscaler EMC effect
III. How the SoLID Spectrometer works.



Context for PVDIS

A comprehensive strategy to understand the origin of matter requires:

The Large Hadron Collider, astrophysical observations ***as well as*** **Lower Energy: $Q^2 << M_Z^2$**

NP/Atomic systems address several topics; unique & complementary:

- ***Neutrino mass and mixing*** *$0\nu\beta\beta$ decay, θ_{13}, β decay, long baseline neutrino expts…*
- ***Rare or Forbidden Processes*** *EDMs, **other LNV, charged LFV**, $0\nu\beta\beta$ decay…*
- ***Dark Matter Searches*** *direct detection, dark photon searches…*
- ***Precision Electroweak Measurements:*** *$(g-2)_\mu$, charged & **neutral current amplitudes***

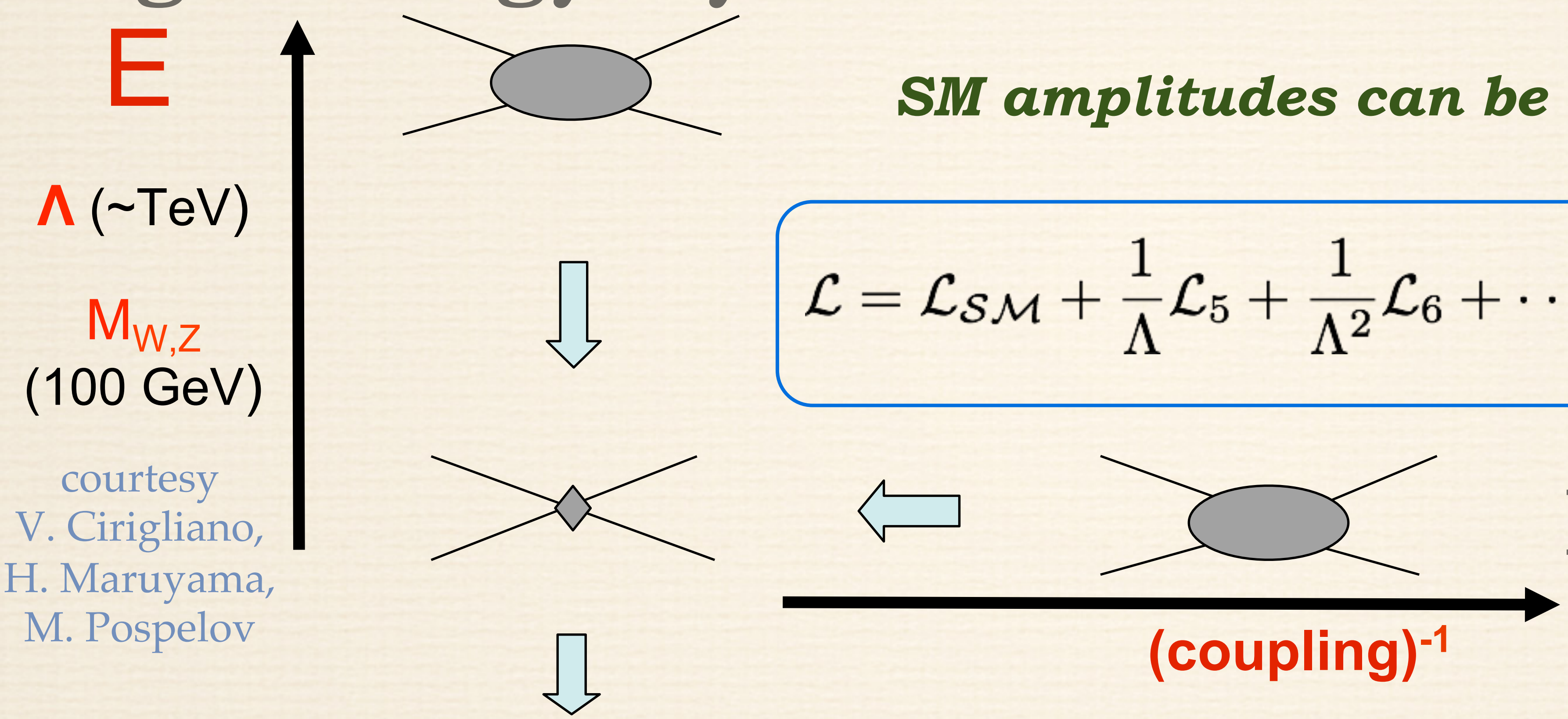
Electroweak Interactions at scales much lower than the W/Z mass

TeV-Scale Probe: Indirect Clues

NP: Fundamental Symmetries; HEP: The Intensity/Precision Frontier

Interplay between electroweak and hadron dynamics

High Energy Dynamics



SM amplitudes can be very precisely predicted

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

higher dimensional operators can be systematically classified

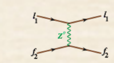
courtesy V. Cirigliano, H. Maruyama, M. Pospelov

Examples: Heavy Z's, light (dark) Z's, technicolor, compositeness, extra dimensions, new ideas???, ...

How can the Standard Model, with all of its holes, predict precision measurements so well??

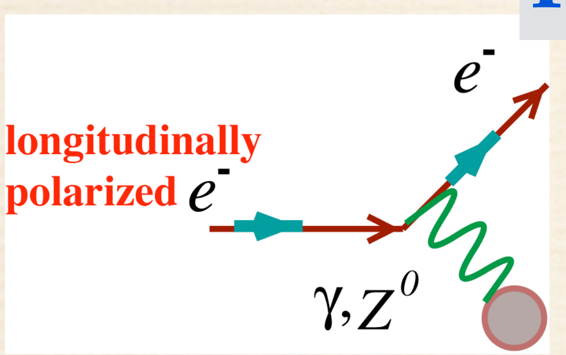
PVES: Example of Weak Neutral Current Interactions

- Precision Neutrino Scattering
- New Physics/Weak-Electromagnetic Interference



- *opposite parity transitions in heavy atoms*
- *Spin-dependent electron scattering*

Parity-violating Electron Scattering



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

g_V and g_A are function of $\sin^2\theta_W$

$$A_{PV} \sim 10^{-5} \cdot Q^2 \quad to \quad 10^{-4} \cdot Q^2$$

Specific choices of kinematics and target nuclei probes different physics:

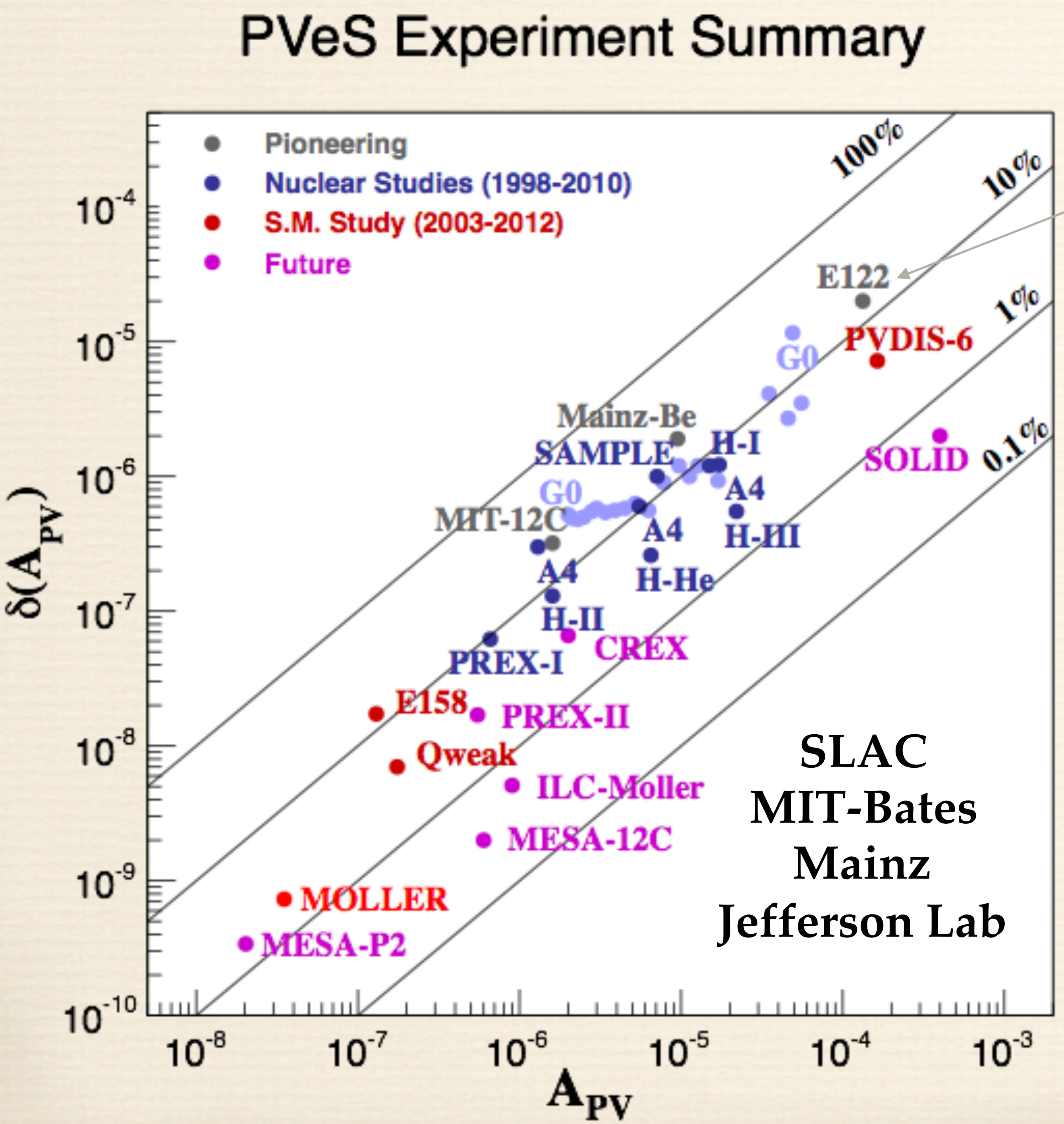
- ***In mid 70s, goal was to show $\sin^2\theta_W$ was the same as in neutrino scattering***
- ***Since early 90's: target couplings probe novel aspects of hadron structure (strange quark form factors, neutron RMS radius of nuclei)***
- ***Future: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale, and novel aspects of nucleon structure***

Continuous interplay between probing hadron structure and electroweak physics

4 Decades of Progress

Parity-violating electron scattering has become a precision tool

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors



Pioneering electron-quark PV DIS experiment SLAC E122

State-of-the-art:

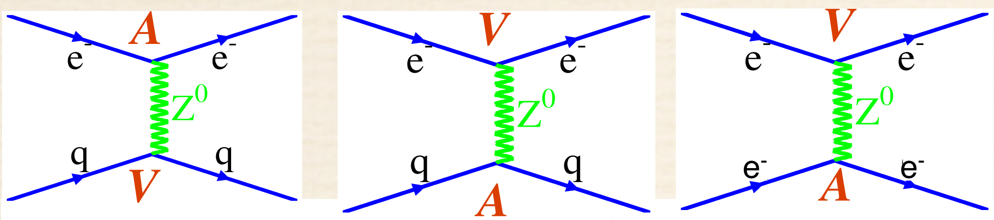
- *sub-part per billion statistical reach and systematic control*
- *sub-1% normalization control*

Physics Topics

- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New Interactions*
- *Novel Probes of Nucleon Structure*

Weak Neutral Current Couplings

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)$$
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

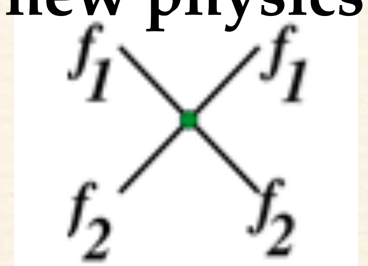


$C_{1i} \equiv 2g_A^e g_V^i$ $C_{2i} \equiv 2g_V^e g_A^i$ $C_{ee} = 2g_V^e g_A^e$

$$C_{1u} = -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W \approx -0.19$$
$$C_{1d} = \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W \approx 0.35$$
$$C_{2u} = -\tfrac{1}{2}+2\sin^2\theta_W \approx -0.04$$
$$C_{2d} = \tfrac{1}{2}-2\sin^2\theta_W \approx 0.04$$

$$C_{ee} = \frac{1}{2} - 2\sin^2\theta_W \approx 0.02$$

+ **new physics**



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

Two equivalent notations!

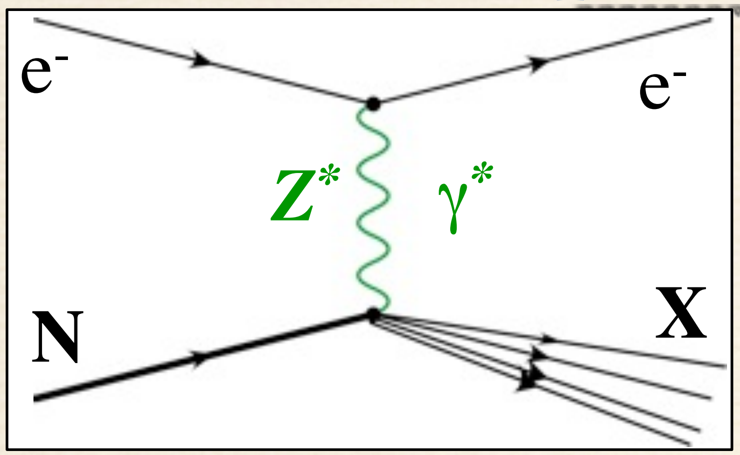
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ ⇒ ***PV elastic e-p scattering, Atomic parity violation***

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ ⇒ ***PV deep inelastic scattering***

$$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$$ ⇒ ***PV Møller scattering***

PV Deep Inelastic Scattering

off the simplest isoscalar nucleus and at high Bjorken x



$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

$Q^2 >> 1\ GeV^2$, $W^2 >> 4\ GeV^2$

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x,Q^2) = \sigma^l/\sigma^r \approx 0.2$$

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

$$A_{\text{iso}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5 + R_s}$$

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

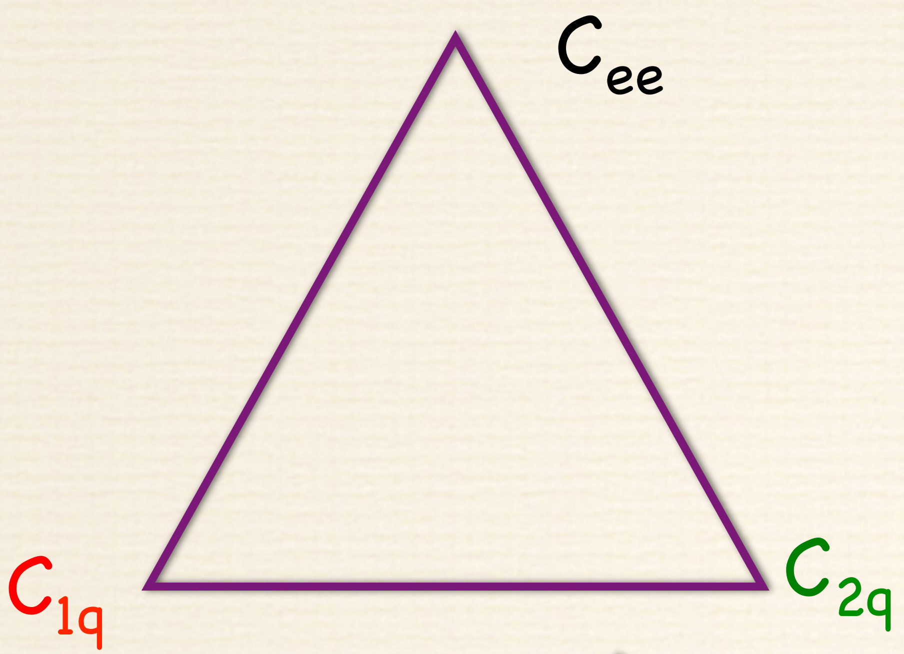
$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

Interplay with QCD

- Parton distributions (u, d, s, c)
- Charge Symmetry Violation (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)

PVES Initiatives: Complementarity



Different experiments address different vertices of the triangle which in turn address different new physics.

SUSY Loops → Q_W^e and Q_W^p:same absolute shift, smaller for others

GUT Z’ → High for Q_W(Cs), Q_W^e(relative), smaller for others

Leptophobic Z’ → axial-quark couplings (C_2’s) only

RPV SUSY → Different for all four in sign and magnitude

Leptoquarks → semi-leptonic only; different sensitivities

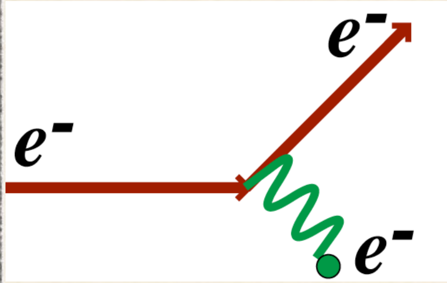
H++ → Q_W^e only

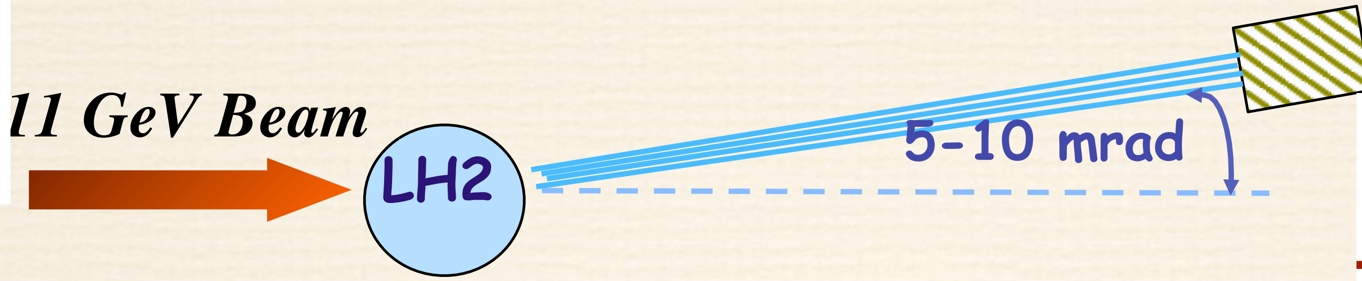
Using Møller scattering (purely leptonic!), improve on E158 by a factor of 5

11 GeV Møller scattering

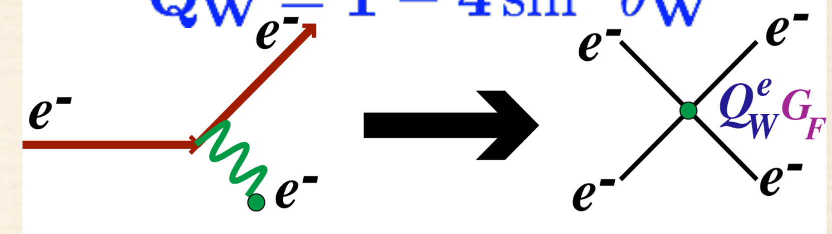
MOLLER at JLab

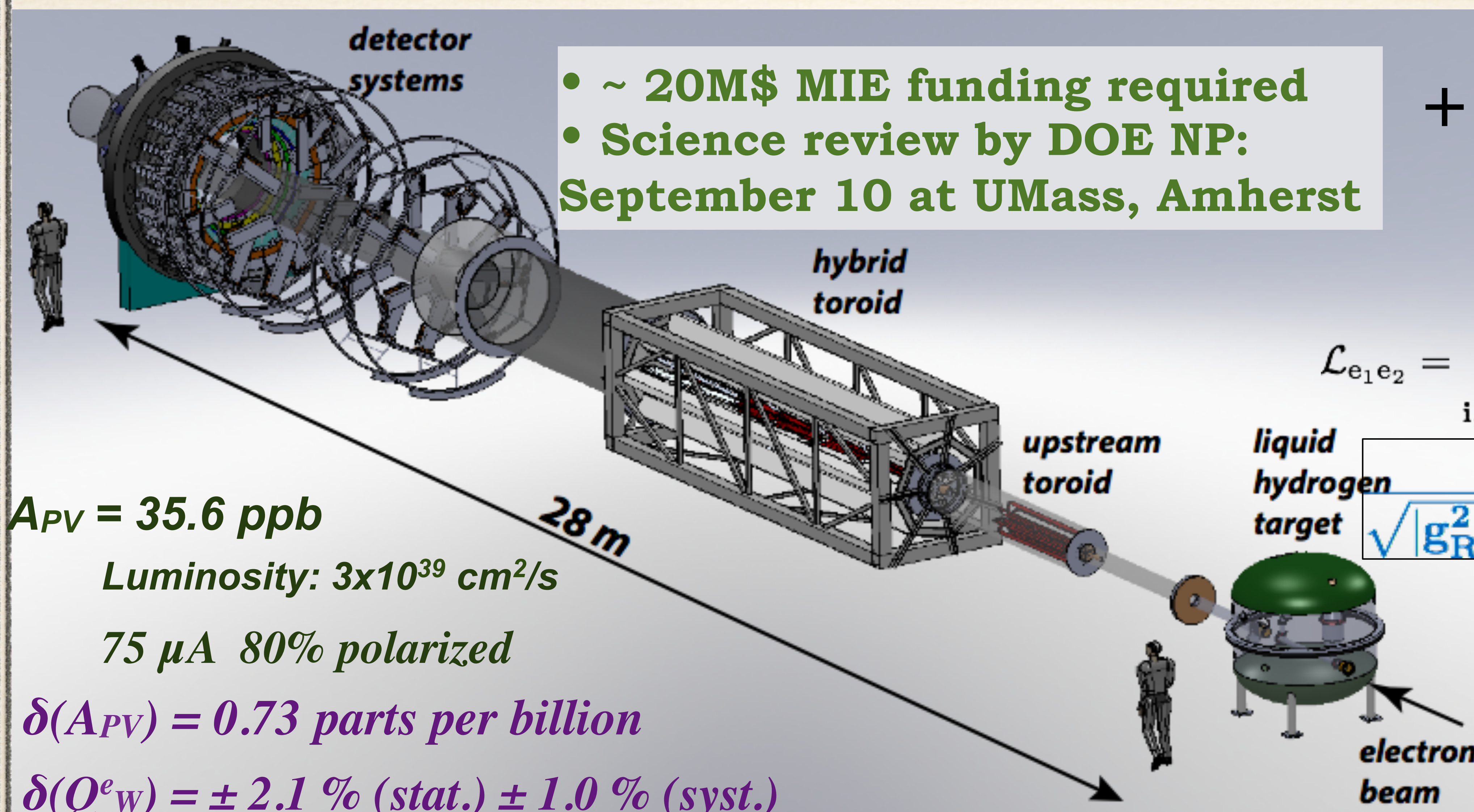
Measurement Of Lepton Lepton Electroweak Reaction





$Q_W = 1 - 4\sin^2\theta_W$





- ~ 20M$ MIE funding required
- Science review by DOE NP: September 10 at UMass, Amherst

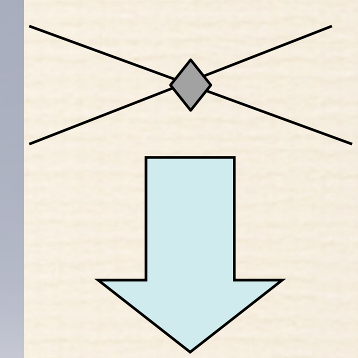
A_{PV} = 35.6 ppb

Luminosity: 3x10^{39} cm^2/s

75 μA 80% polarized

$\delta(A_{PV})$ = 0.73 parts per billion

$\delta(Q^e_W) = \pm\, 2.1\,\%$ (stat.) $\pm\, 1.0\,\%$ (syst.)



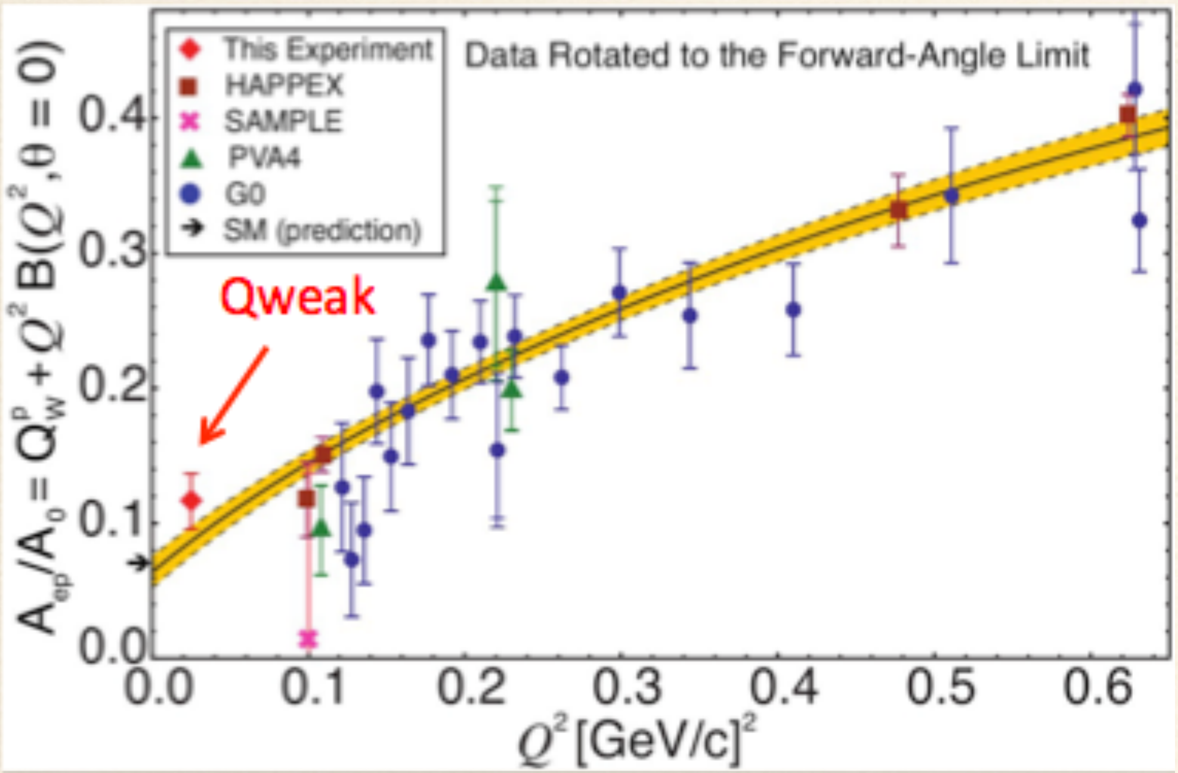
$+ \frac{1}{\Lambda^2}\mathcal{L}_6$

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

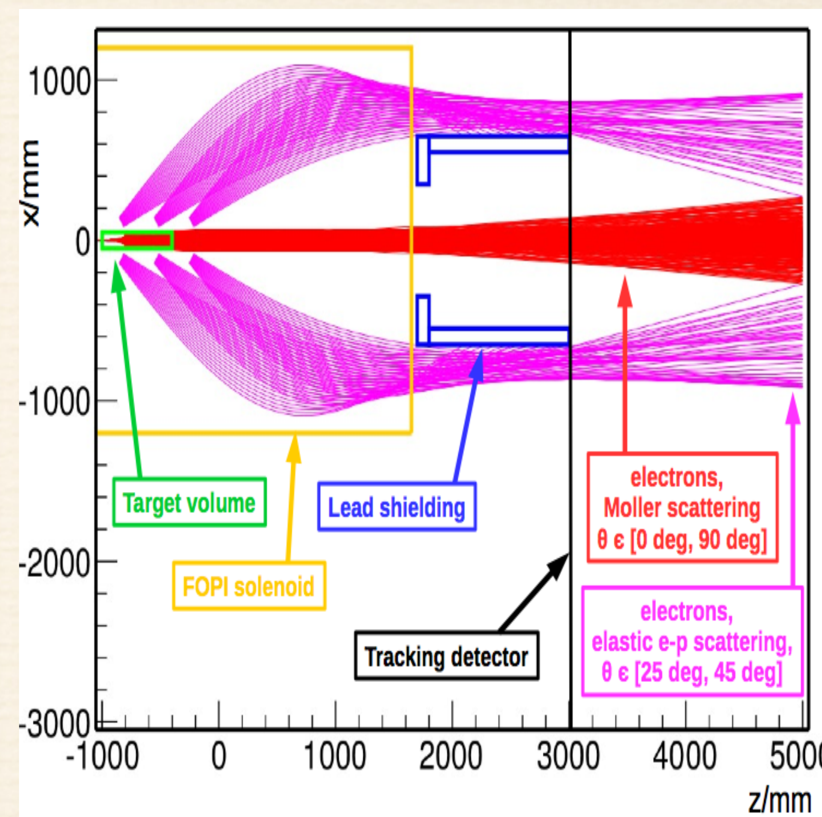
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\ \text{TeV}$$

The Weak Charge of the Proton

*



$$Q^p_{weak} = 2C_{1u} + C_{1d} \quad \propto 1 - 4\sin^2\vartheta_W$$



Two Production Runs: Feb-May ’11, Nov ’11-May ‘12

Run 0 Results (1/25th of total dataset) – published in PRL **111**, 141803 (2013)

$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb}$ at $\langle Q^2 \rangle = 0.0250\ (\text{GeV}/c)^2$

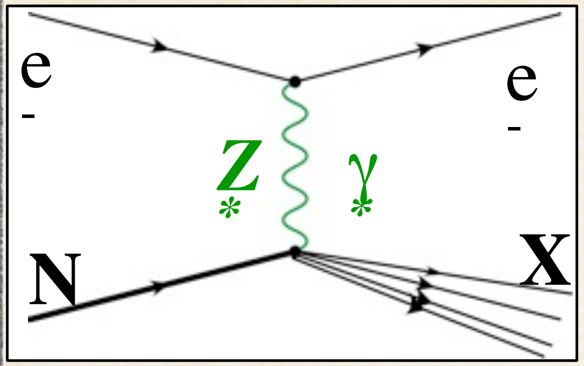
$Q^p_W(\text{PVES}) = 0.064 \pm 0.012$ $\qquad Q^p_W(\text{SM}) = 0.0710 \pm 0.0007$

First determination of proton’s weak charge in good agreement with Standard Model

P2 at MESA at Mainz

PVDIS on LD_2 at 6 GeV

A_{PV} in deep inelastic e-D scattering:



$Q^2 >> 1\ GeV^2$, $W^2 >> 4\ GeV^2$

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

a(x): function of C_{1i}'s

b(x): function of C_{2i}'s

For ^2H, assuming charge symmetry, structure functions cancel in the ratio:

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

Physics Run: Oct-Dec 2010

Wang et al., Nature 506, no. 7486, 67 (2014);

6 GeV run results

$Q^2 \sim 1.1\ GeV^2$

A^{phys} (ppm)	−91.10
(stat.)	±3.11
(syst.)	±2.97
(total)	±4.30

$Q^2 \sim 1.9\ GeV^2$

	Asymmetry
A^{phys} (ppm)	−160.80
(stat.)	±6.39
(syst.)	±3.12
(total)	±7.12

PARTICLE PHYSICS

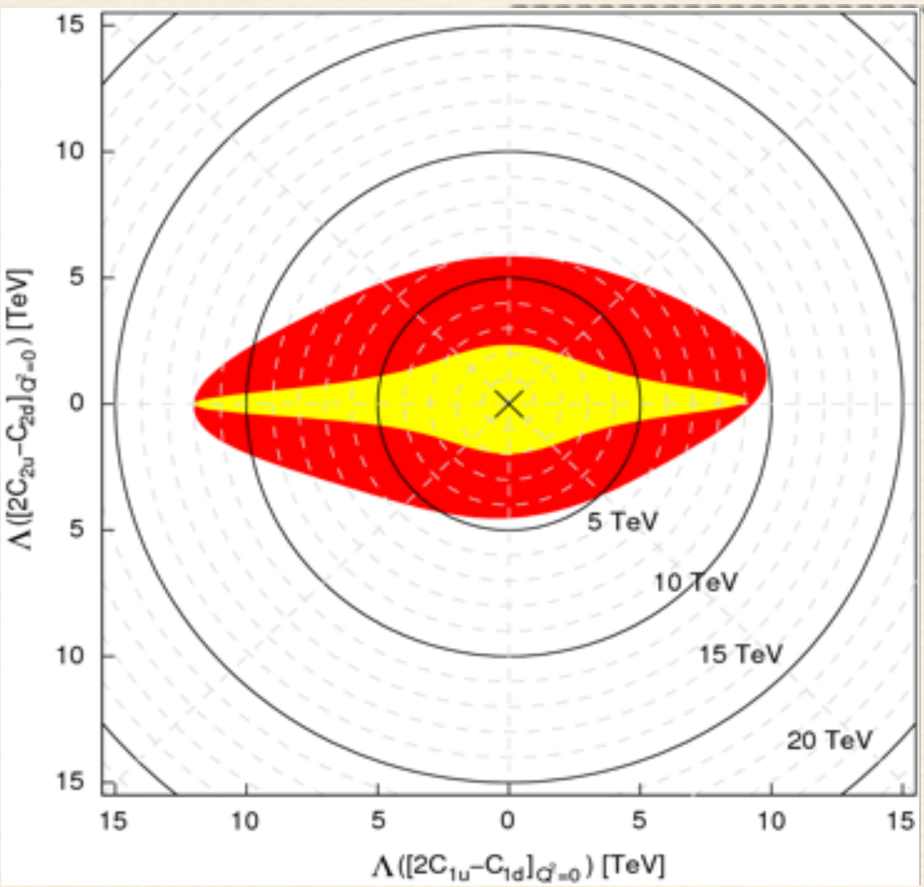
Quarks are not ambidextrous

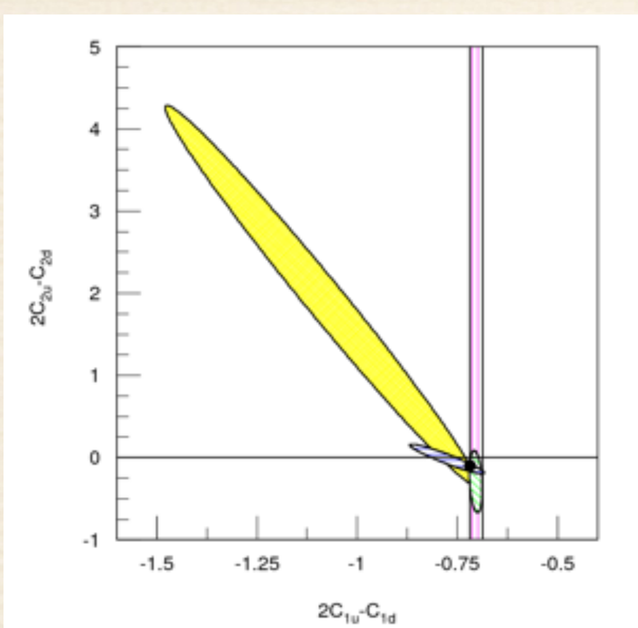
W. Marciano article in Nature

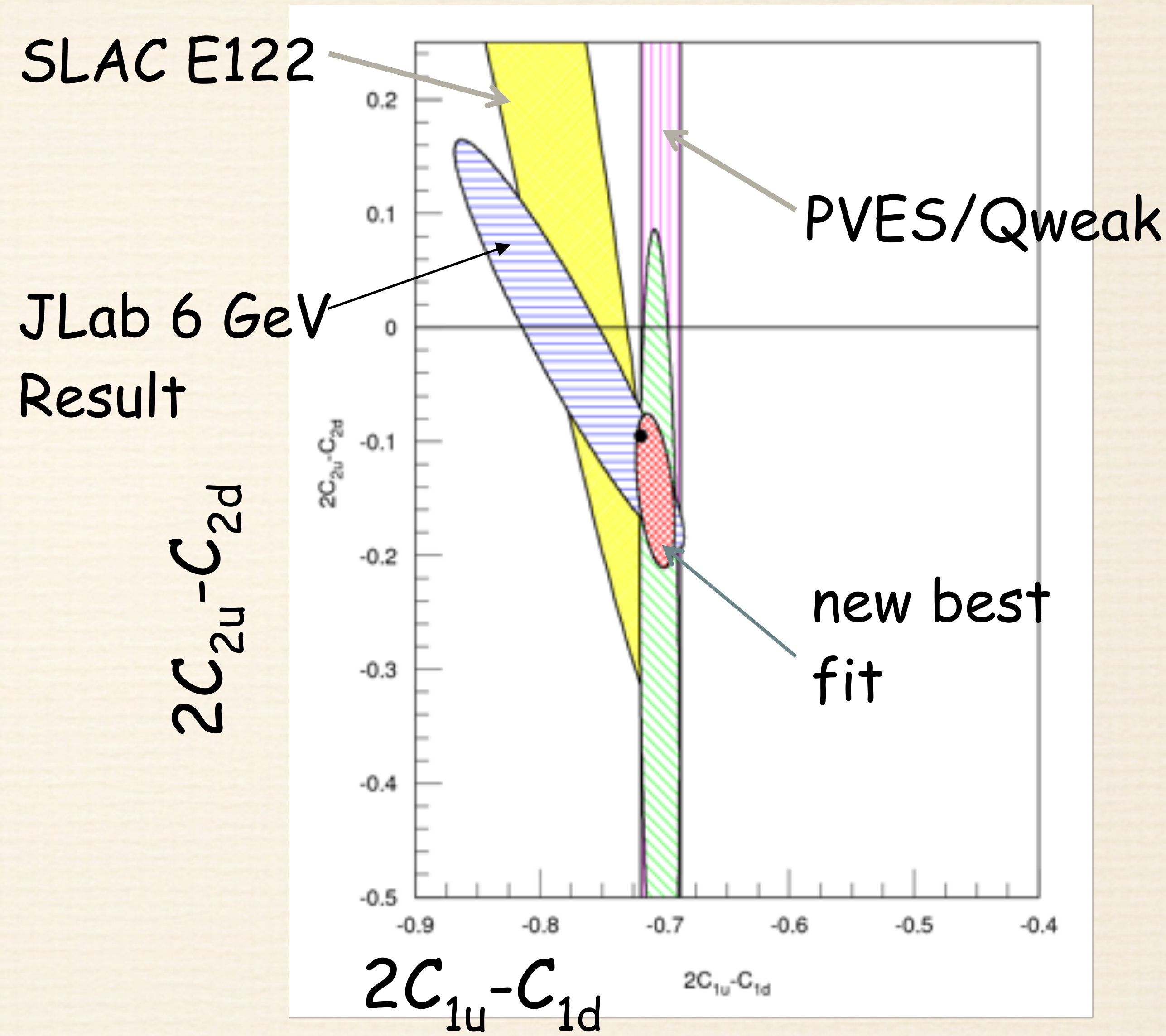
By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. SEE LETTER P.67

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

Implications

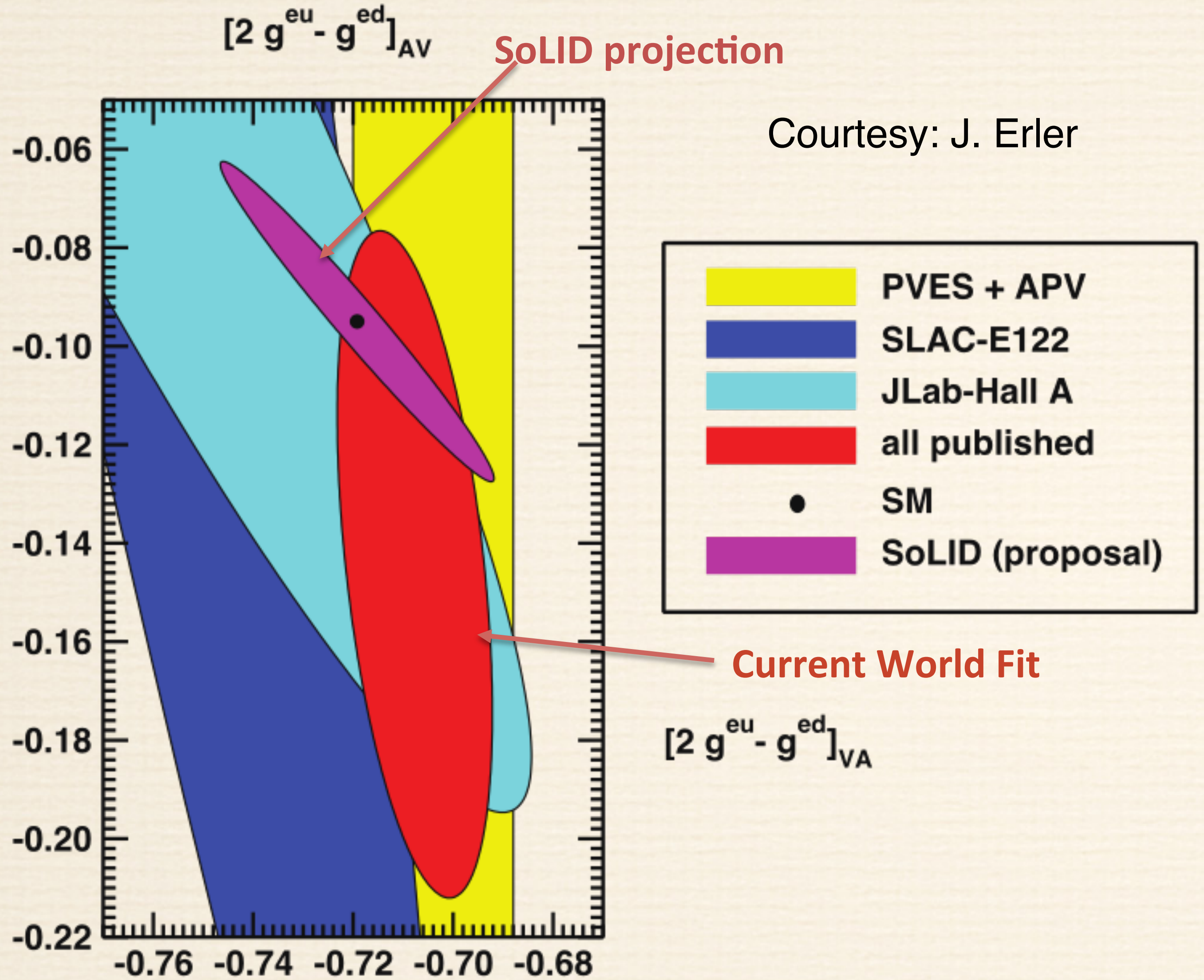


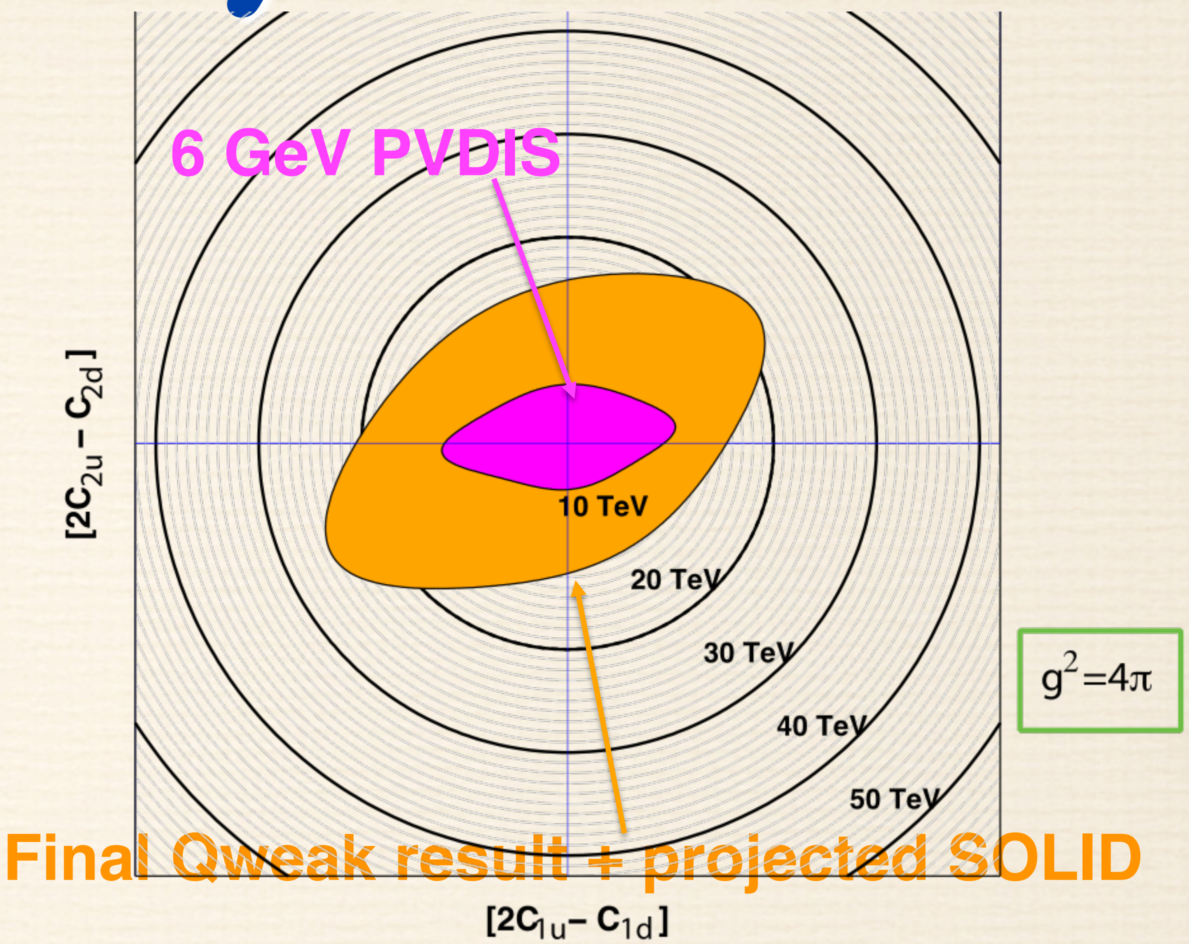




first experimental determination that an axial quark coupling combination is non-zero (as predicted)

SOLID New Physics Sensitivity



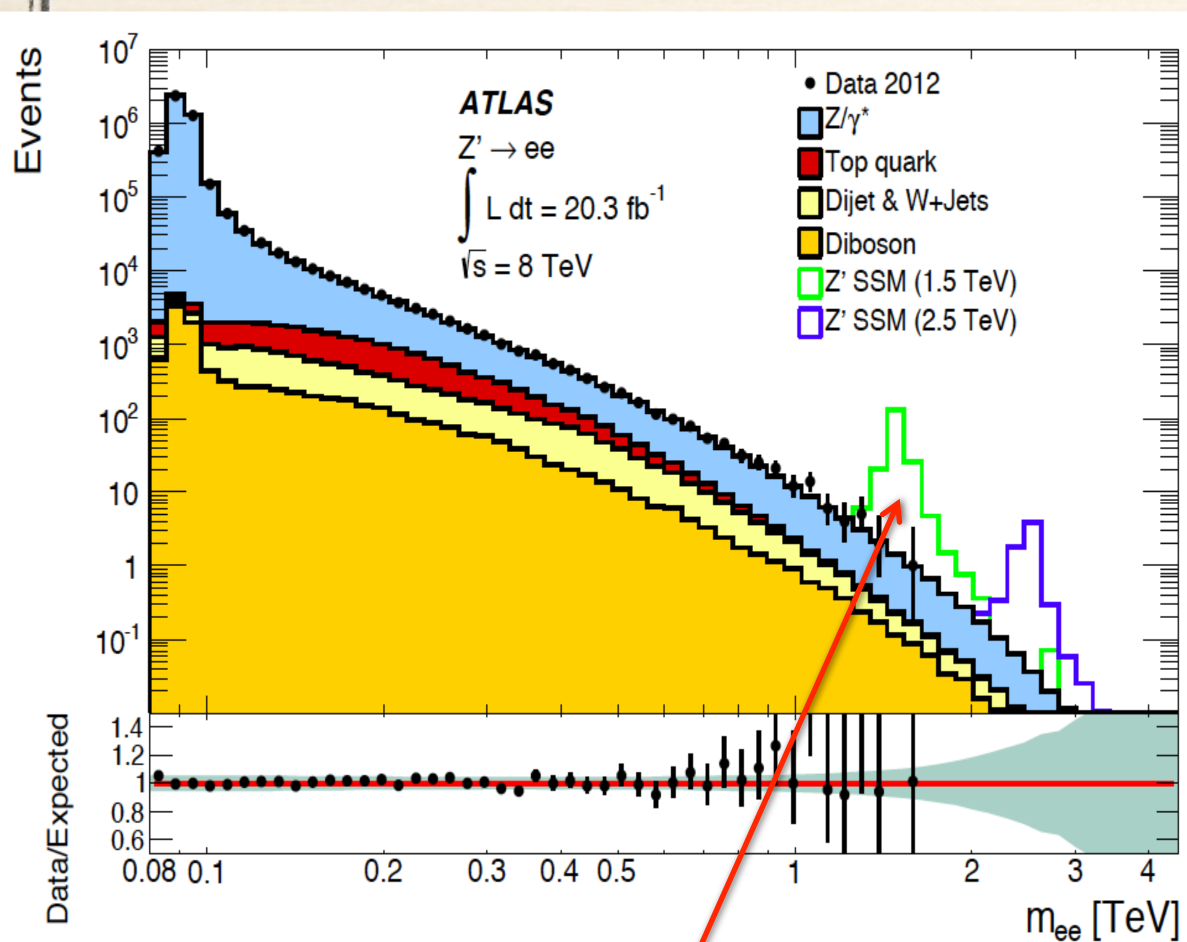


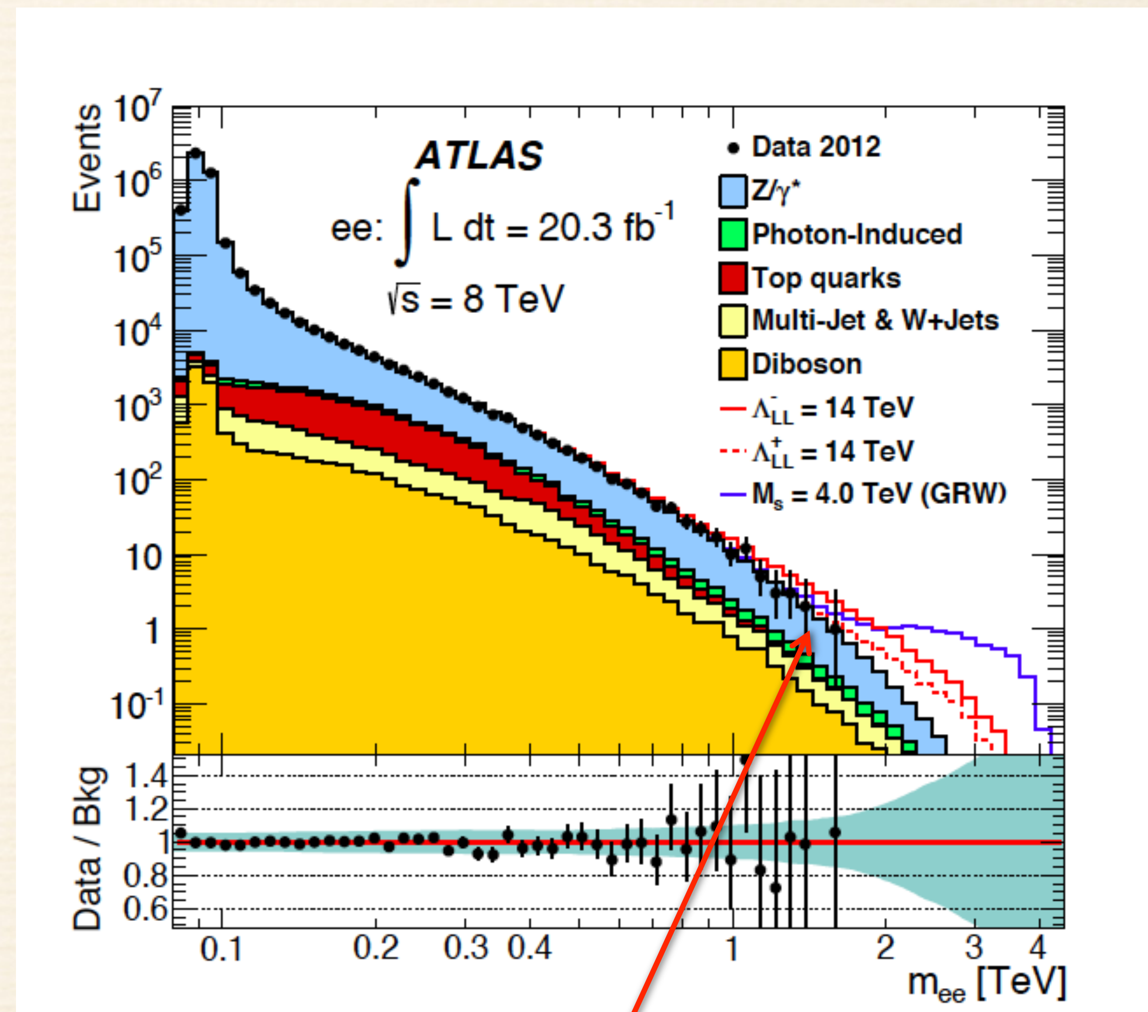
Qweak and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

Z’ versus Compositeness

Issue: PVDIS determines g^2/Λ^2:

LHC sensitivity to g^2/Λ^2 depends on Λ.





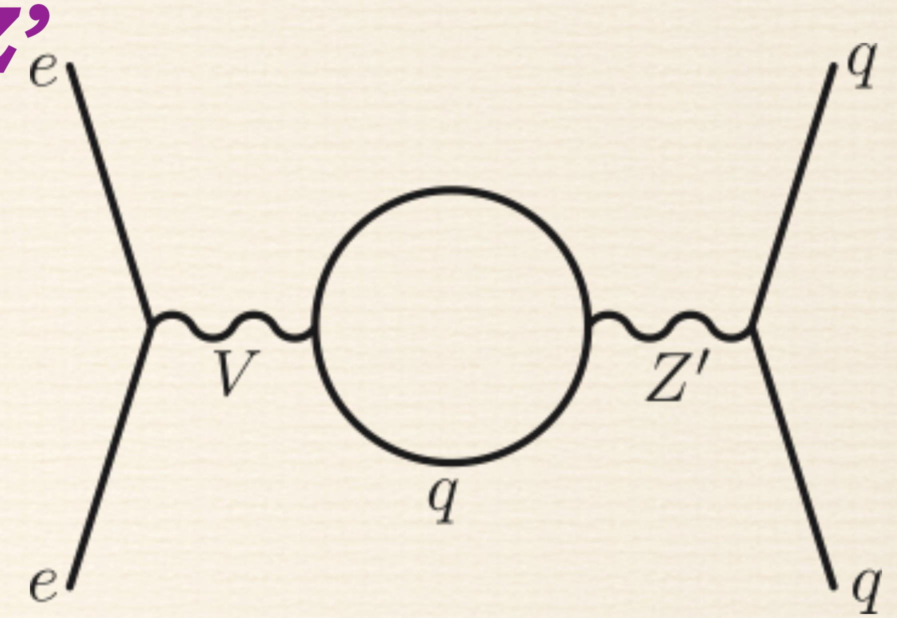
Signal dominates

Are Z’s fat because they decay to invisible particles or b’s?

Noise dominates

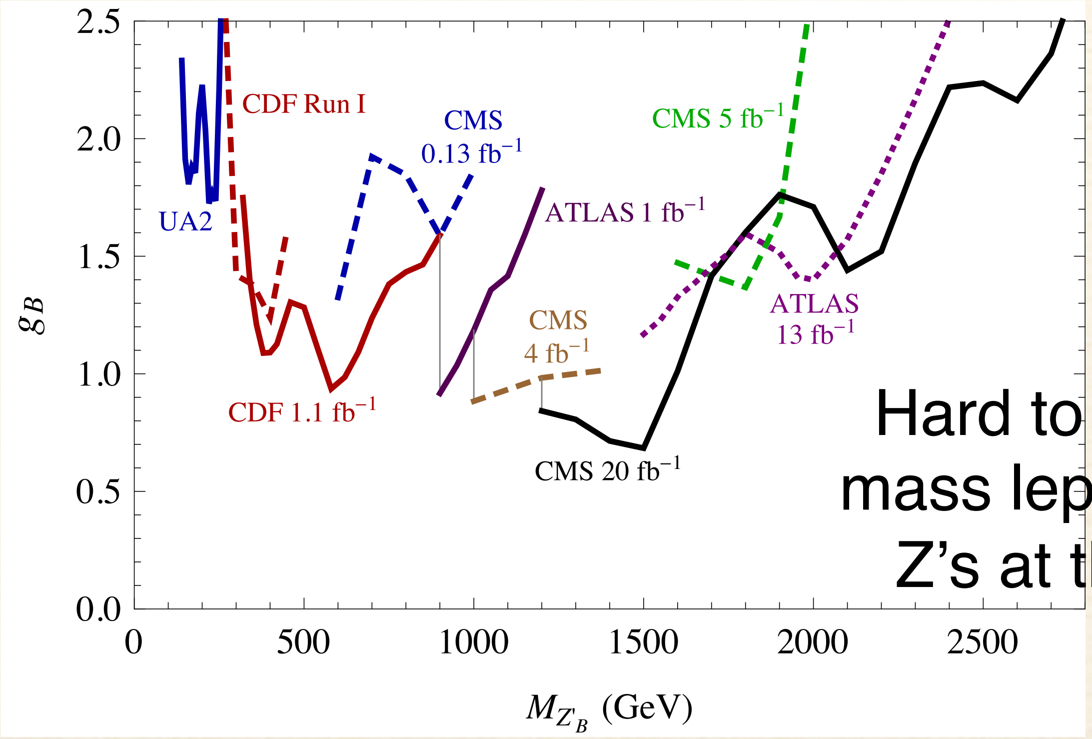
Unique SoLID Sensitivity

Leptophobic Z'



- *Virtually all GUT models predict new Z's*
- *LHC reach ~ 5 TeV, but....*
- *Little sensitivity if Z' doesnt couple to leptons*
- *Leptophobic Z' as light as 120 GeV might escape detection*
- *Leptophobic Z' might couple to ark matter*

arXiv:1203.1102v1
Buckley and Ramsey-Musolf



Hard to see low mass lepto-phobic Z's at the LHC

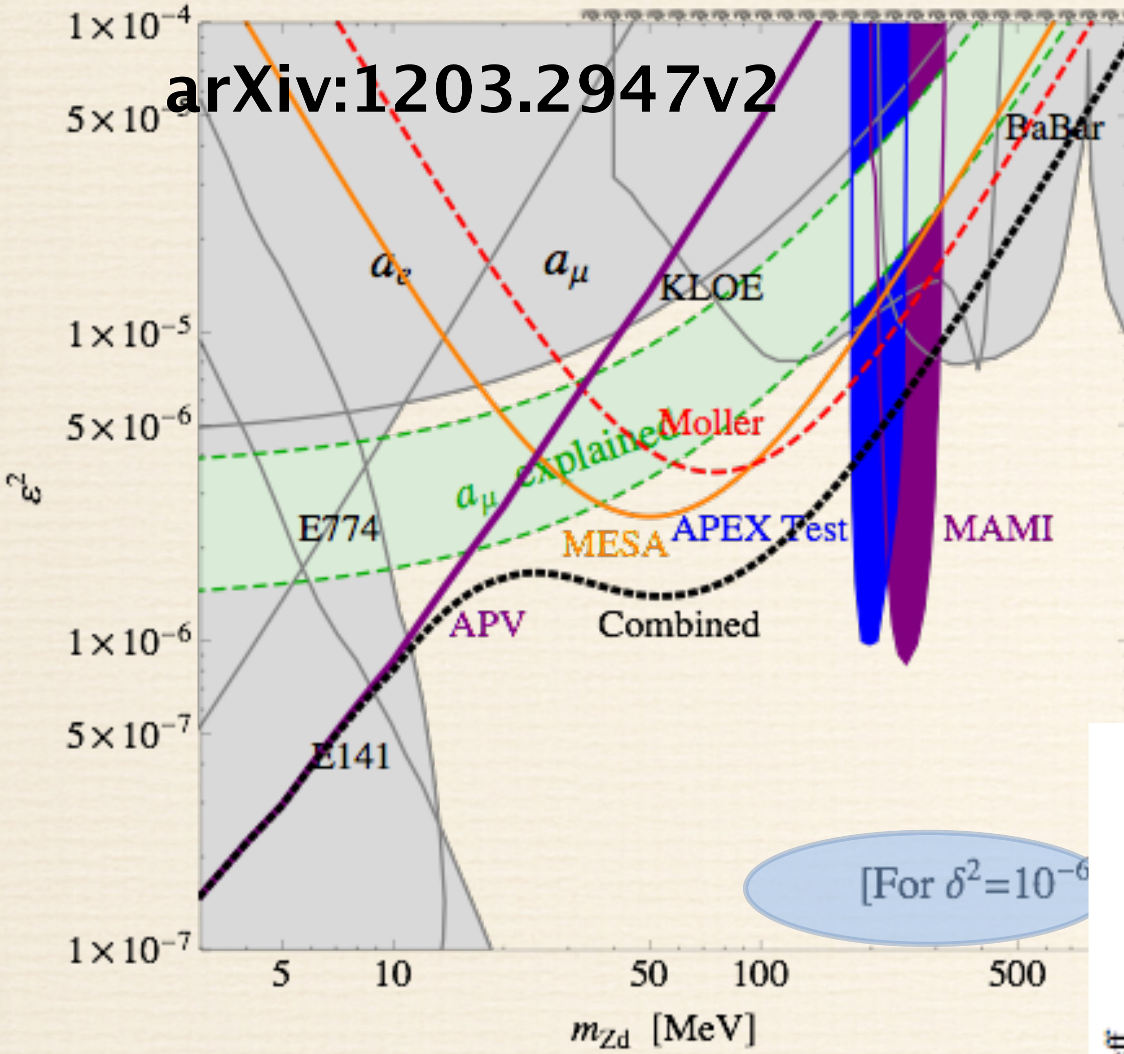
*Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect **C_{2q}'s***

SOLID can improve sensitivity: 100-200 GeV range

Dark Z to Invisible Particles

Davoudiasl, Lee, Marciano

arXiv:1203.2947v2



Dark Photons:

Beyond kinetic mixing; introduce mass mixing with the Z^0

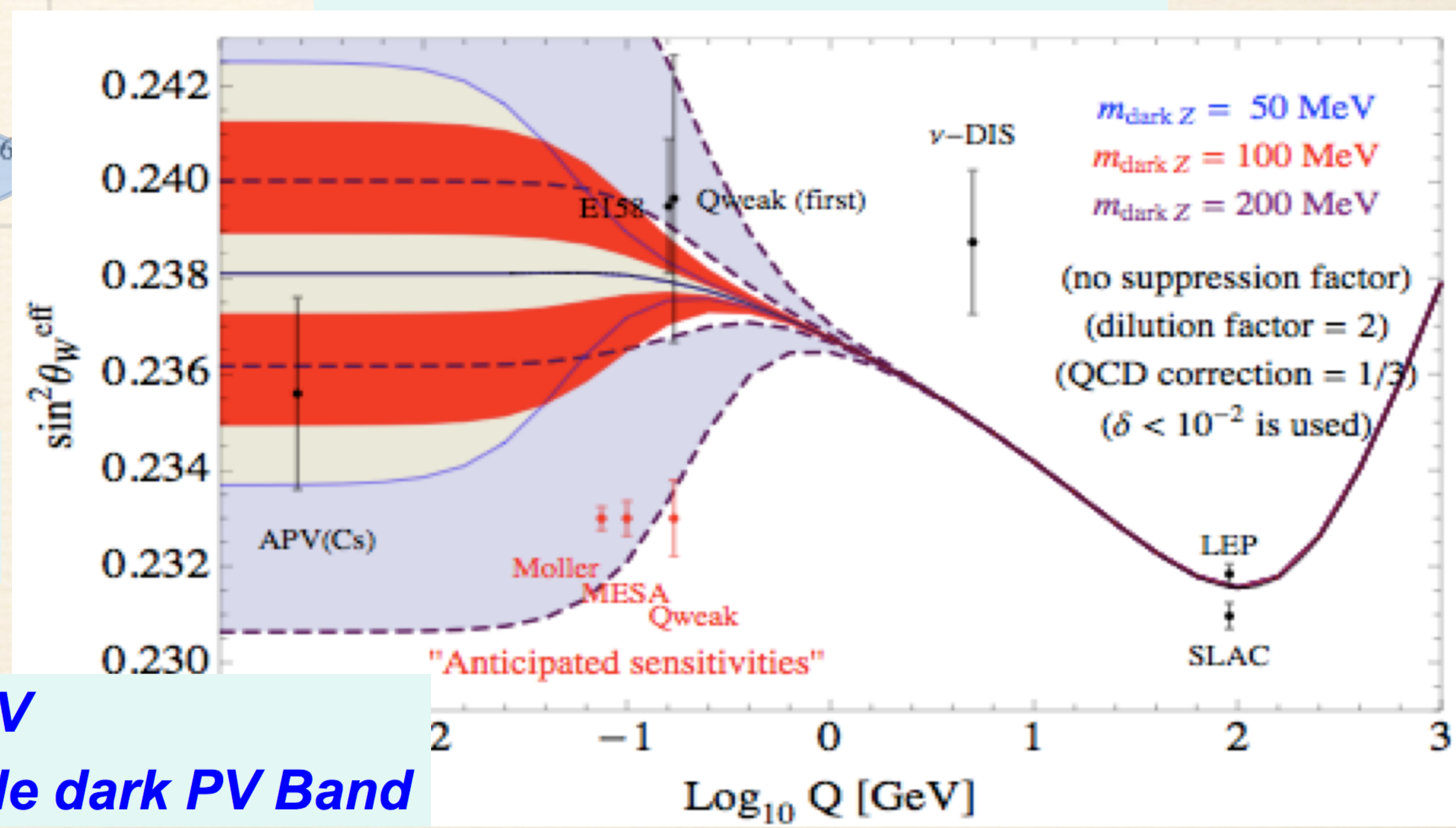
$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$

- Potentially Observable Effects (for $\delta \geq 10^{-3}$)

  APV & Polarized Electron Scattering at low <Q>

  $BR(K \rightarrow \pi Z_d) \approx 4\text{x}10^{-4}\delta^2$ $BR(B \rightarrow K Z_d) \approx 0.1\delta^2$

δ^2 roughly probed to 10^{-6}



$K \rightarrow \pi Z_d \rightarrow \pi$+"missing energy"

ε and δ effects could partially cancel!

Suppression by ~1/6 allows Z_d~100MeV

Combined with muon g-2 → observable dark PV Band

QCD Physics with PVDIS

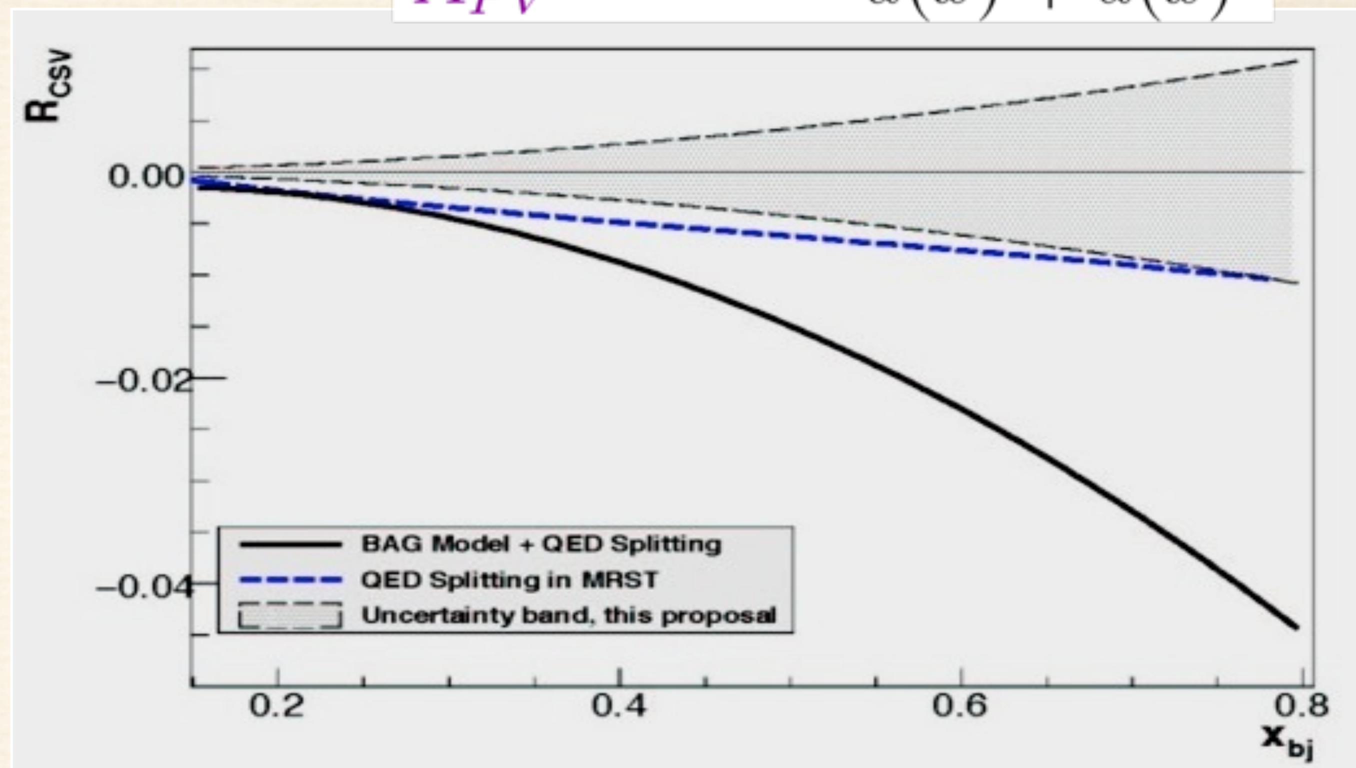
$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

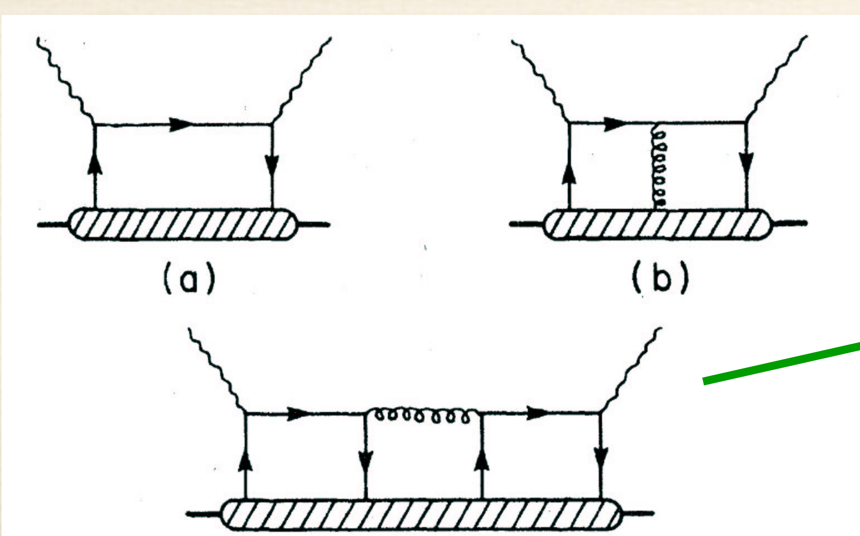
$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

We already know CSV exists:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

- **Direct sensitivity to parton-level CSV**
- **Important implications for PDF's**
- ***Could be* partial explanation of the NuTeV anomaly**





Castorina & Mulders, '84

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

Zero in quark-parton model

Higher-Twist valence quark-quark correlation

(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

Cloet, Bentz, Thomas, arXiv 0901.3559

^{48}Ca PVDIS

Consider PVDIS on a heavy nucleus

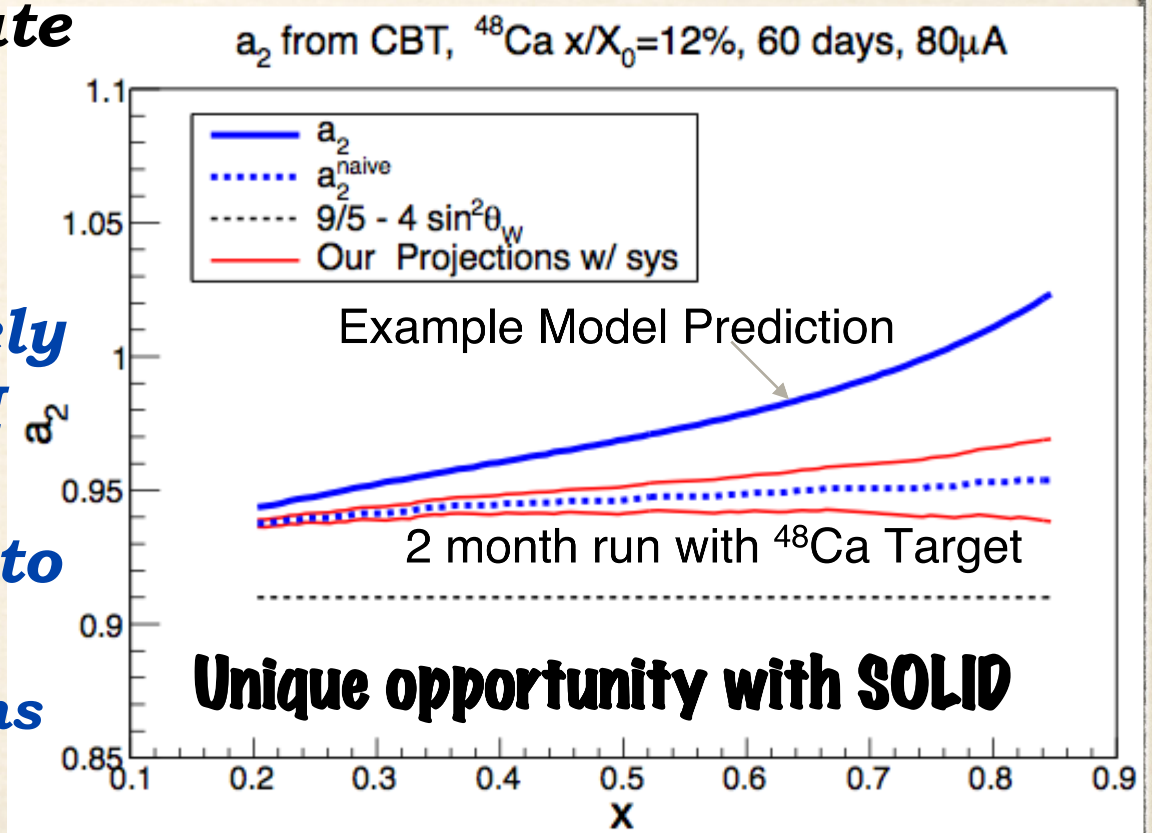
- Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange): shifts quark distributions: "apparent" charge symmetry violation
- Isovector EMC effect: explain additional 2/3 of NuTeV anomaly

- **new insight into medium modification of quark distributions**

$$a_2 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \cdots$$

Great leverage for a clean isospin decomposition of the EMC effect in an inclusive measurement

- ***Flavor separation: clean data sparse to date***
- ***With hadrons in the initial or final state, small effects are difficult to disentangle (theoretically and experimentally)***
- ***Precise isotope cross-section ratios in purely electromagnetic electron scattering: MUCH reduced sensitivity to the isovector combination; potentially see small effects to discriminate models***
  - ***a flavor decomposition of medium modifications is extremely challenging***



Longstanding issue in proton structure

Proton PVDIS: d/u at high x

(high power liquid hydrogen target)

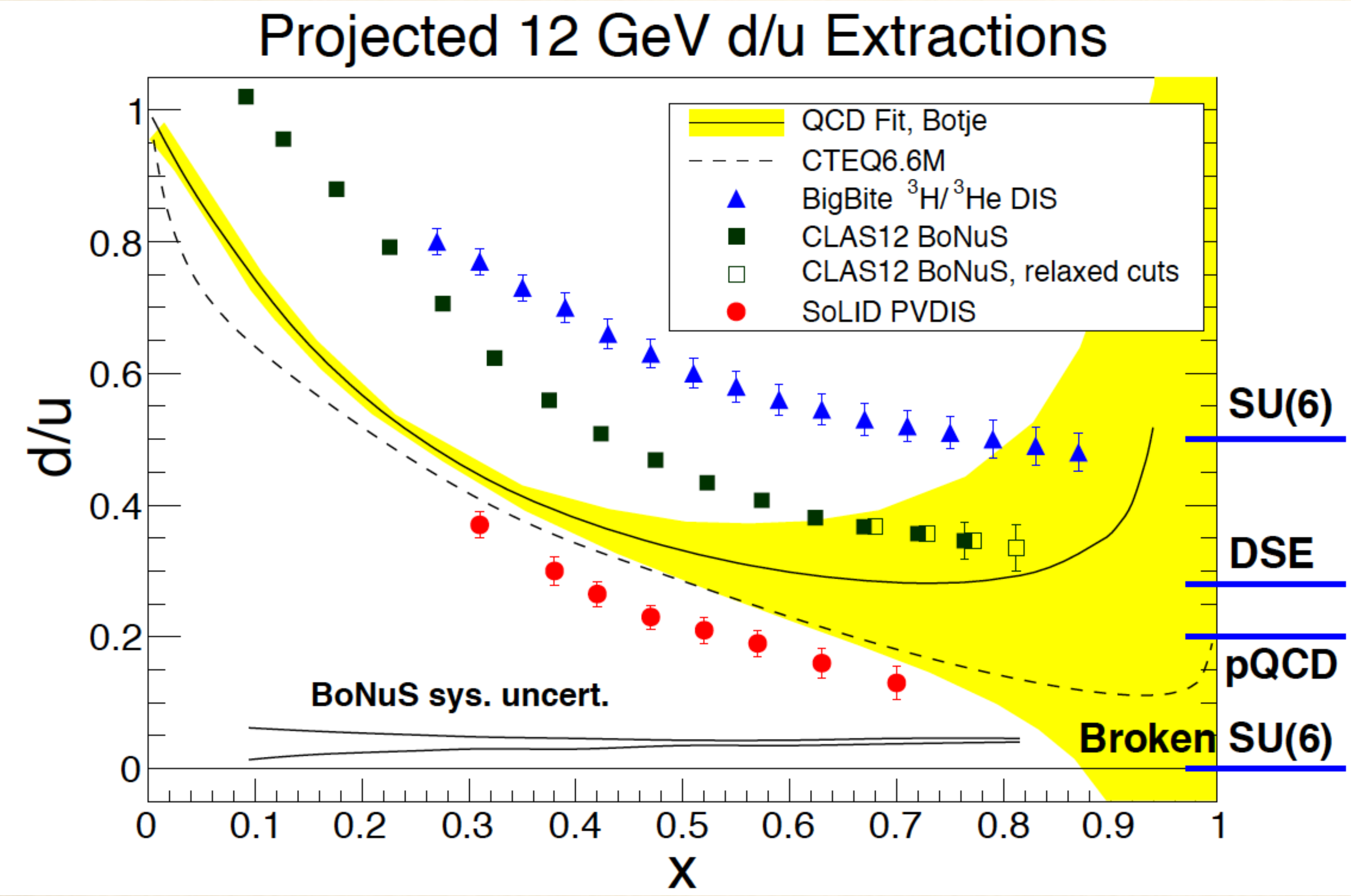
SU(6): d/u~1/2

Broken SU(6): d/u~0

Perturbative QCD: d/u~1/5

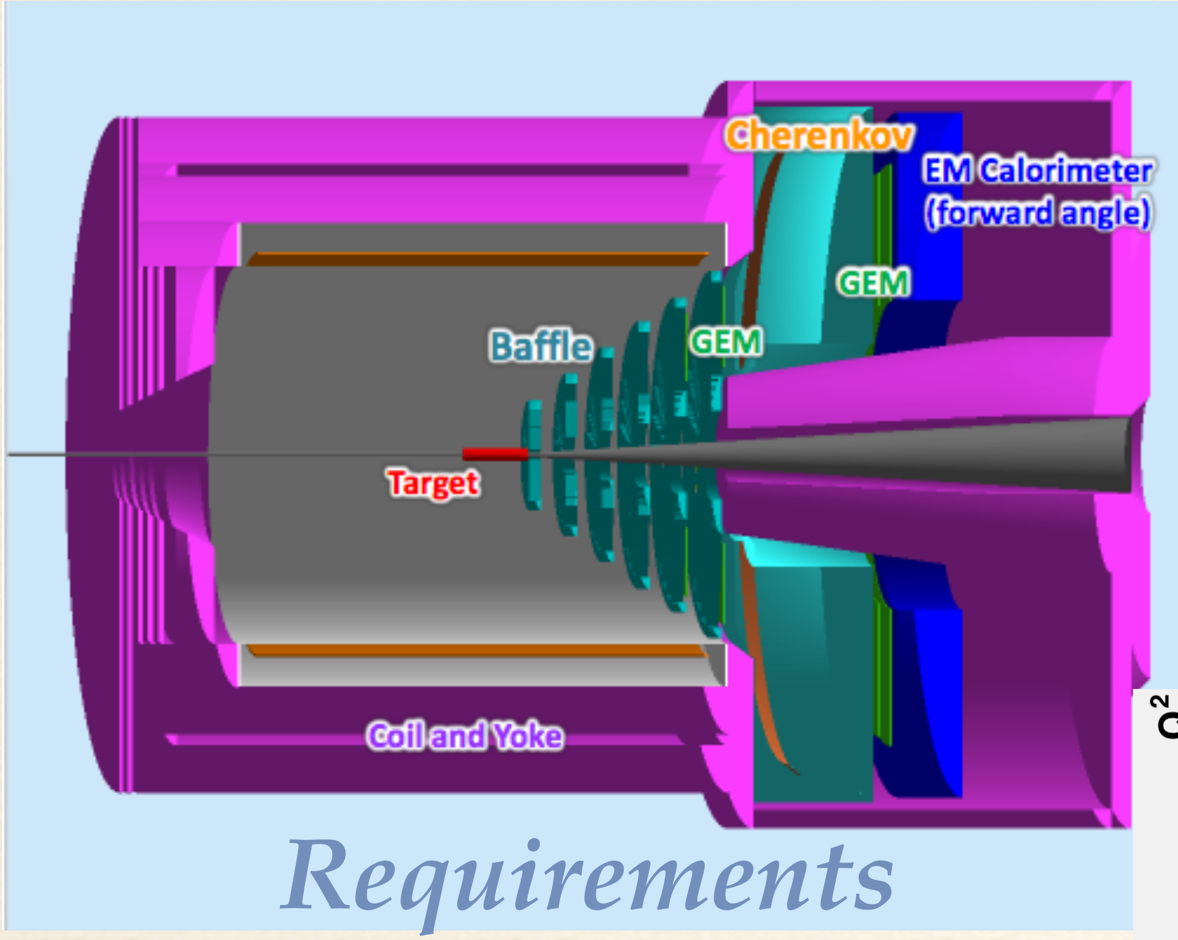
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

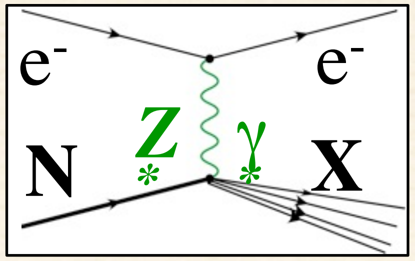
$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$



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

SOLID with the 12 GeV Upgrade



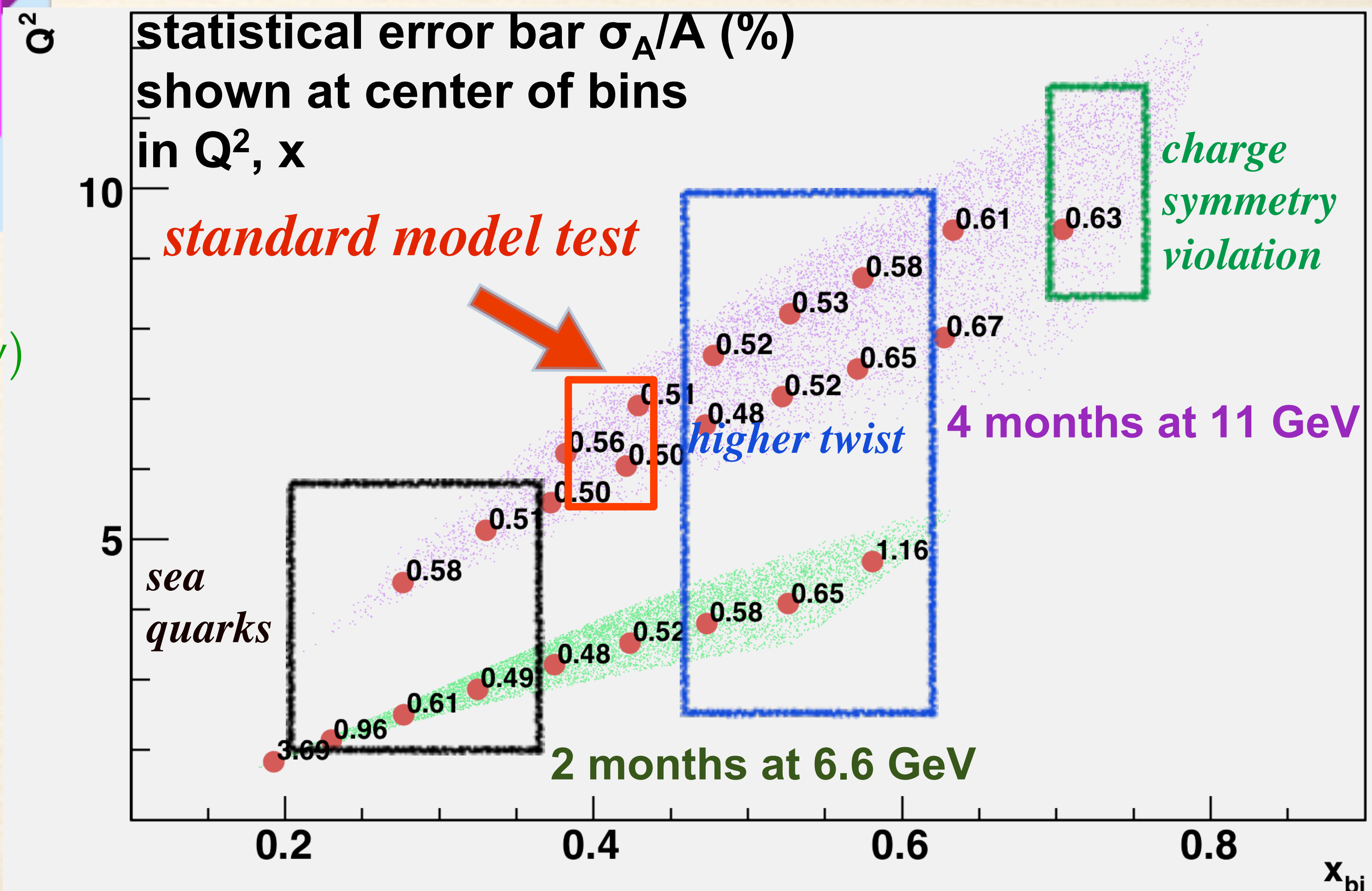


$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

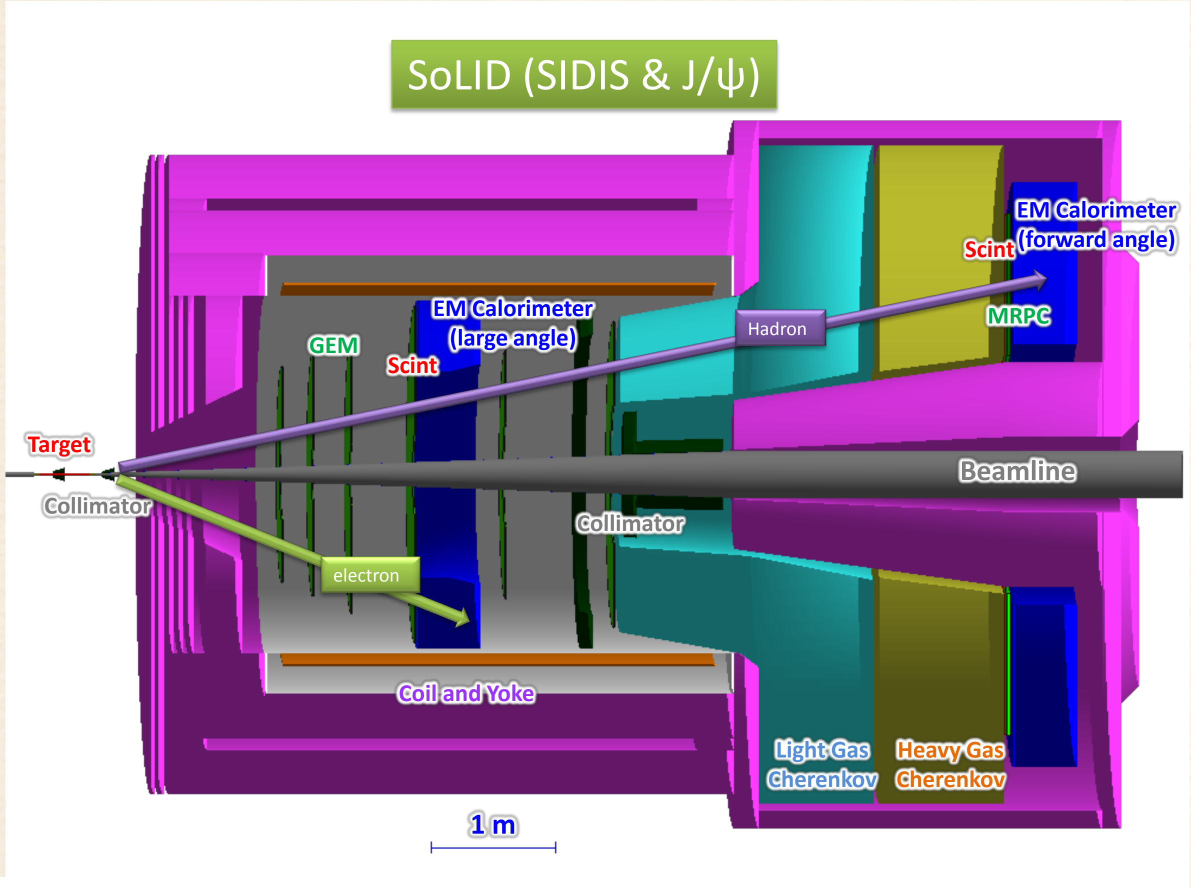
Strategy: **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

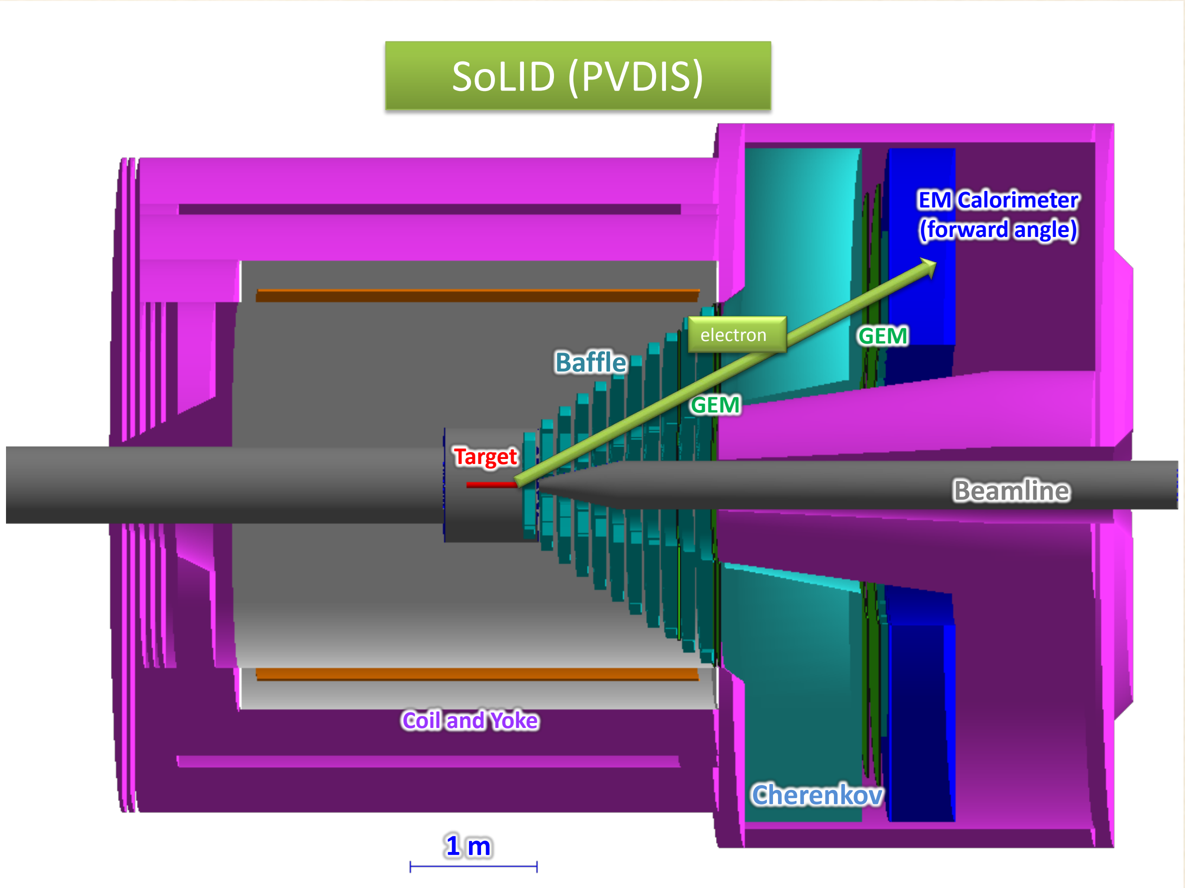
Requirements

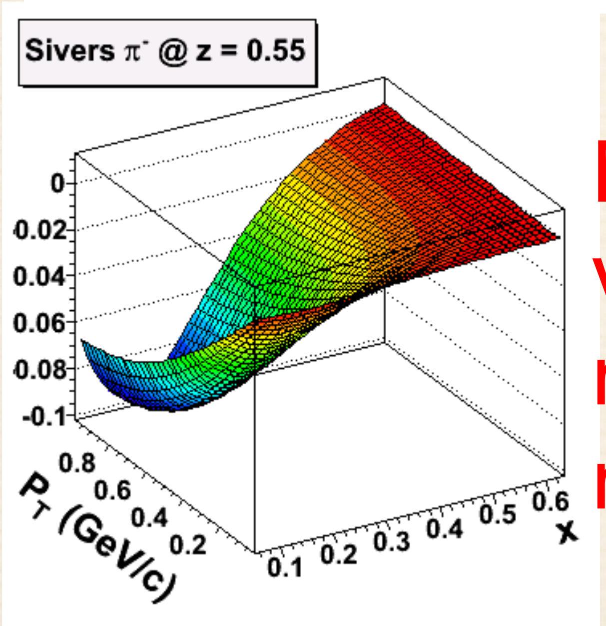
- High Luminosity with E > 10 GeV
- Large scattering angles (for high x & y)
- Better than 1% errors for small bins
- x-range 0.25-0.75
- $W^2 > 4\ GeV^2$
- Q^2 range a factor of 2 for each x
  - (Except at very high x)
- Moderate running times



SoLID is also for SIDIS



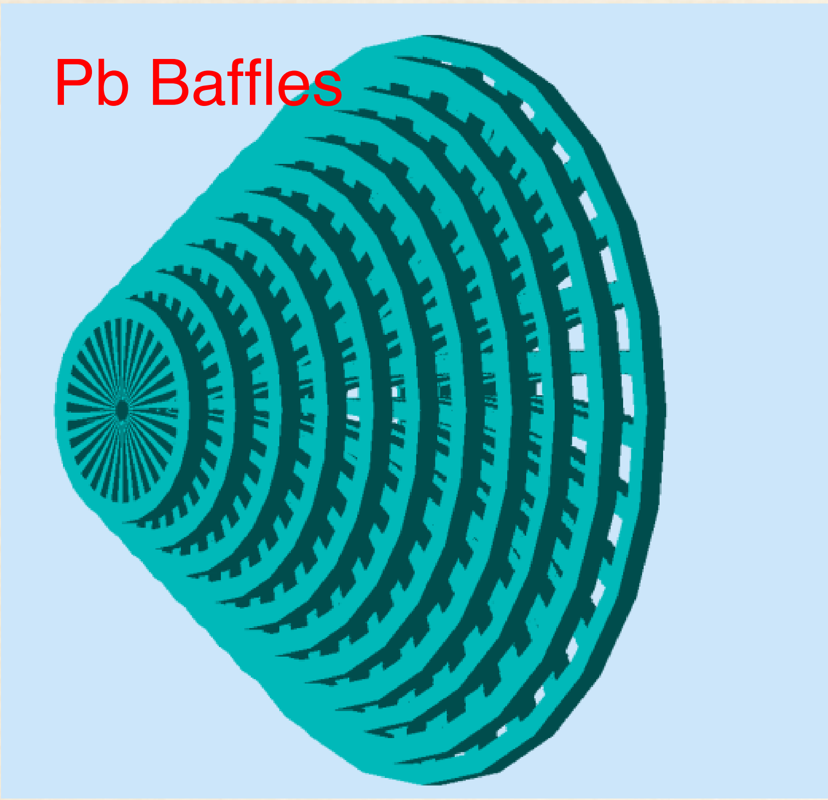


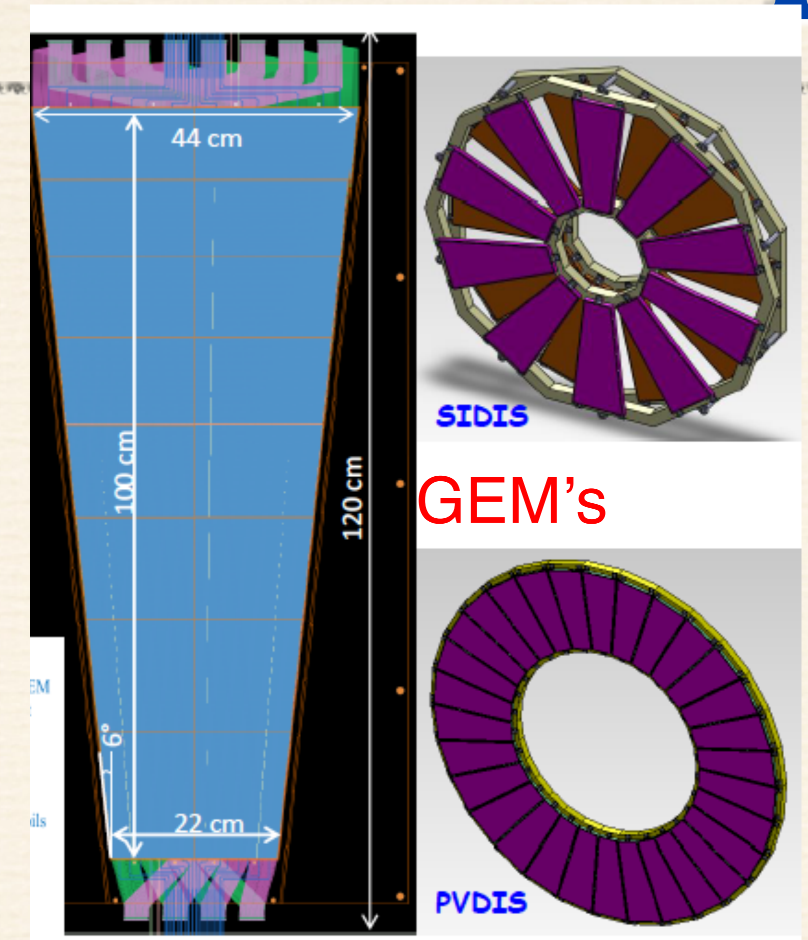


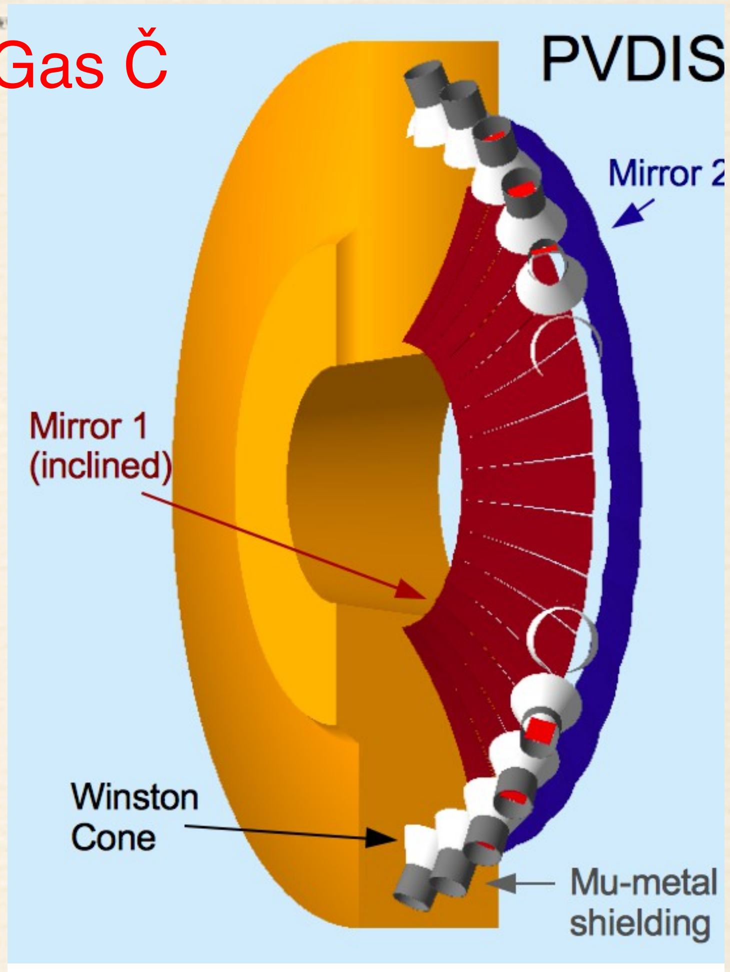
More kinematic variables → more bins→ more data

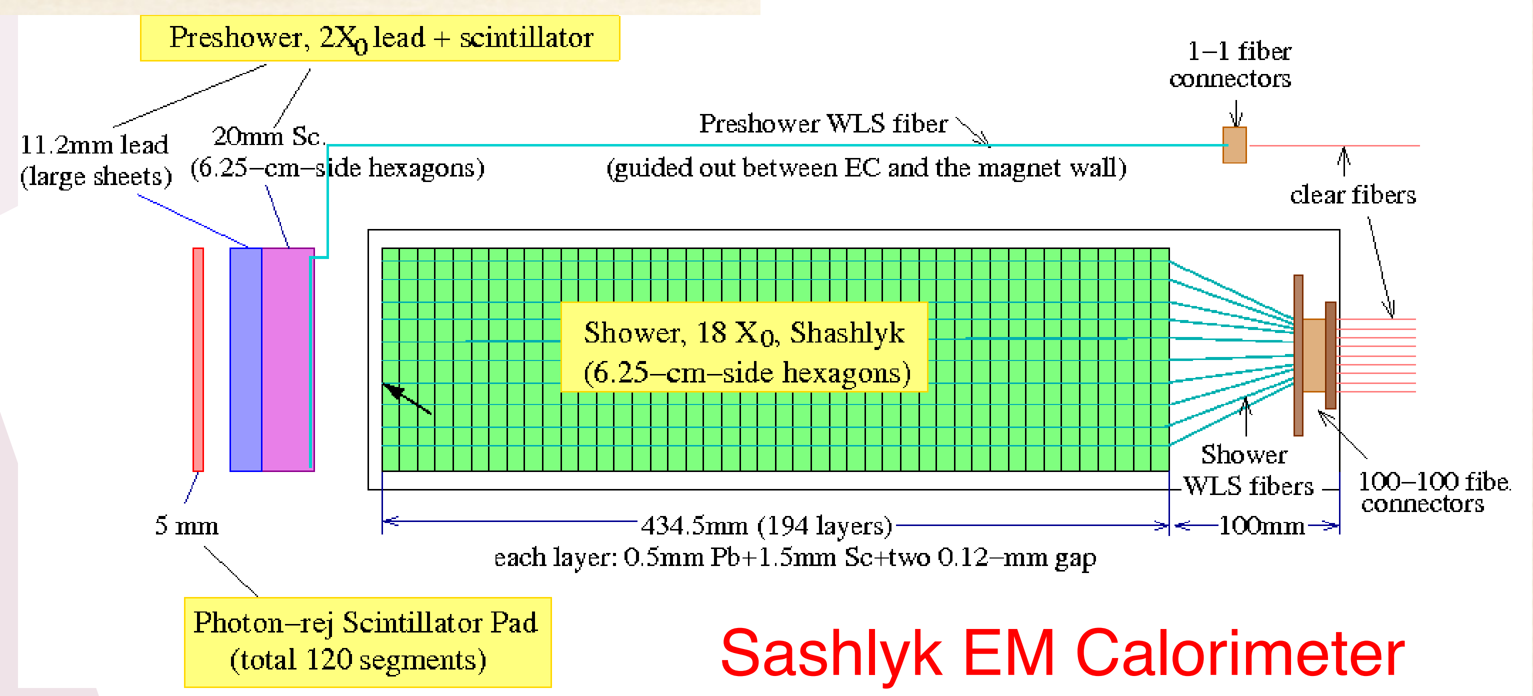
SoLID provides both the large acceptance and the high luminosity required to fully exploit the full potential of the JLab 12 GeV upgrade

Elements of the Apparatus









PMT for Č

Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

Kinematic dependence of physics topics

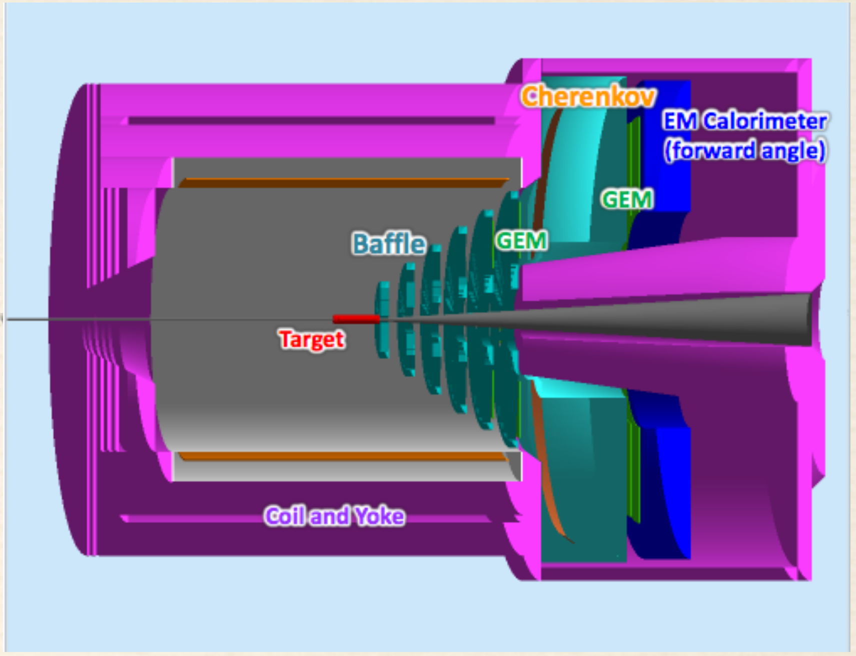
	x	Y	Q^2
New Physics	none	yes	small
CSV	yes	small	small
Higher Twist	large?	no	large

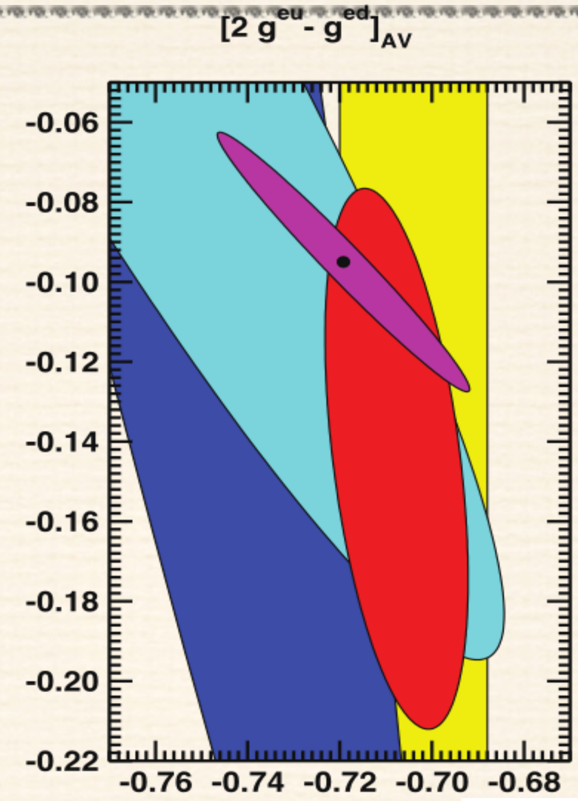
- Measure A_d in **narrow** bins of x, Q^2 with 0.5% precision
- Cover broad Q^2 range for x in [0.3,0.6] to constrain HT
- Search for CSV with x dependence of A_d at high x
- Use $x > 0.4$, high Q^2 to measure a combination of the C_{iq}'s

Fit data to:

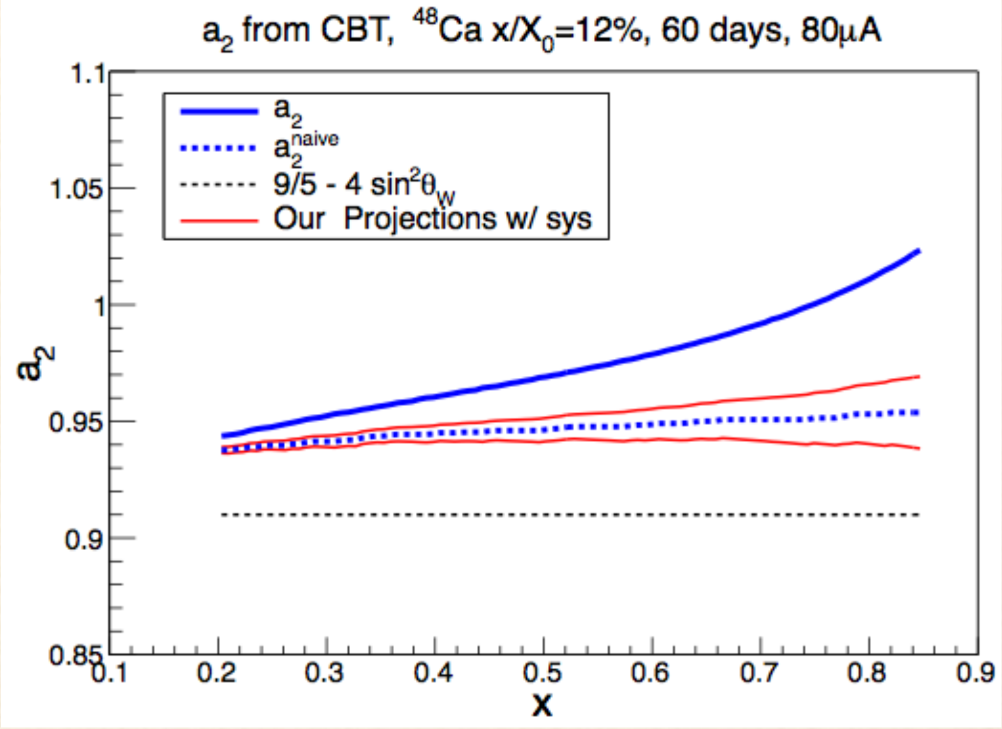
$$A_{\mathrm{Meas.}} = A_{\mathrm{SM}} \left[1 + \frac{\beta_{\mathrm{HT}}}{(1-x)^3 Q^2} + \beta_{\mathrm{CSV}} x^2 \right]$$

Summary





I. PVDIS fills out the EW couplings: where is the new physics hiding???
II. PVDIS provides a unique window on QCD
III. The SoLID Spectrometer fills the need at Jlab for a facility that combines both high acceptance and high intensity.
IV. Next step: Directors review coming soon.



Backup

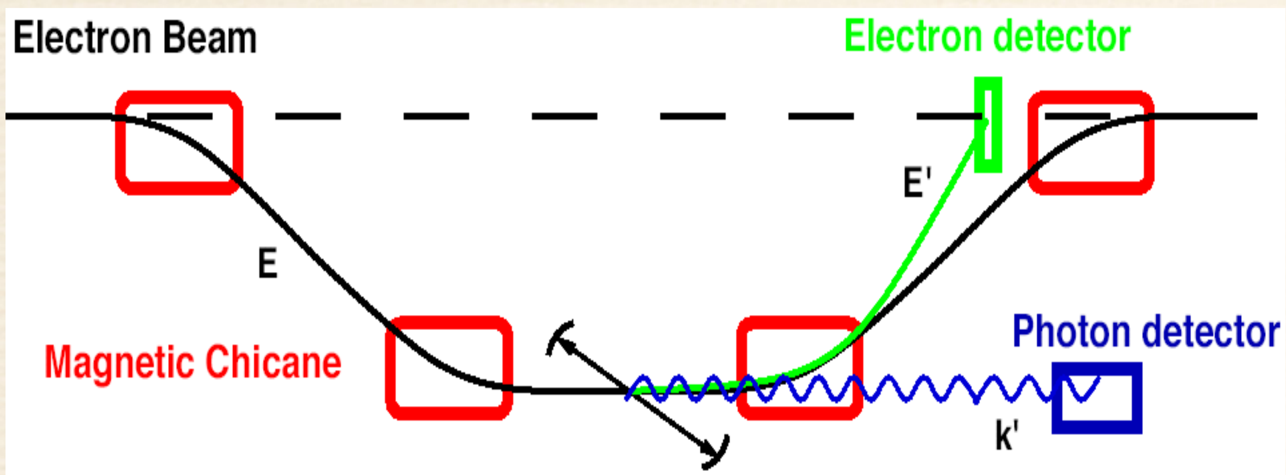
Error Budget (%) and Running time

Total	0.6
Polarimetry	0.4
Q2	0.2
Radiative Corrections	0.2
Event reconstruction	0.2
Statistics	0.3

Energy(GeV)	4.4	6.6	11	Test
Days(LD2)	18	60	120	27
Days(LH2)	9	-	90	14

180 Days are Approved

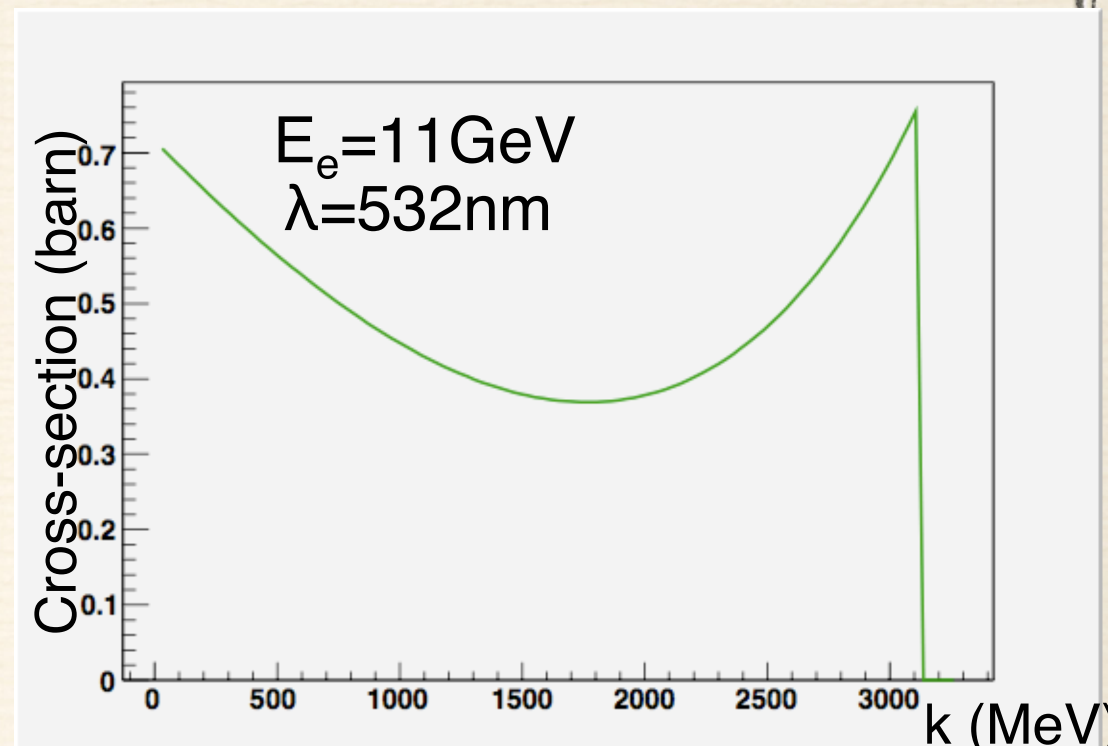
Prcision Compton Polarimetry

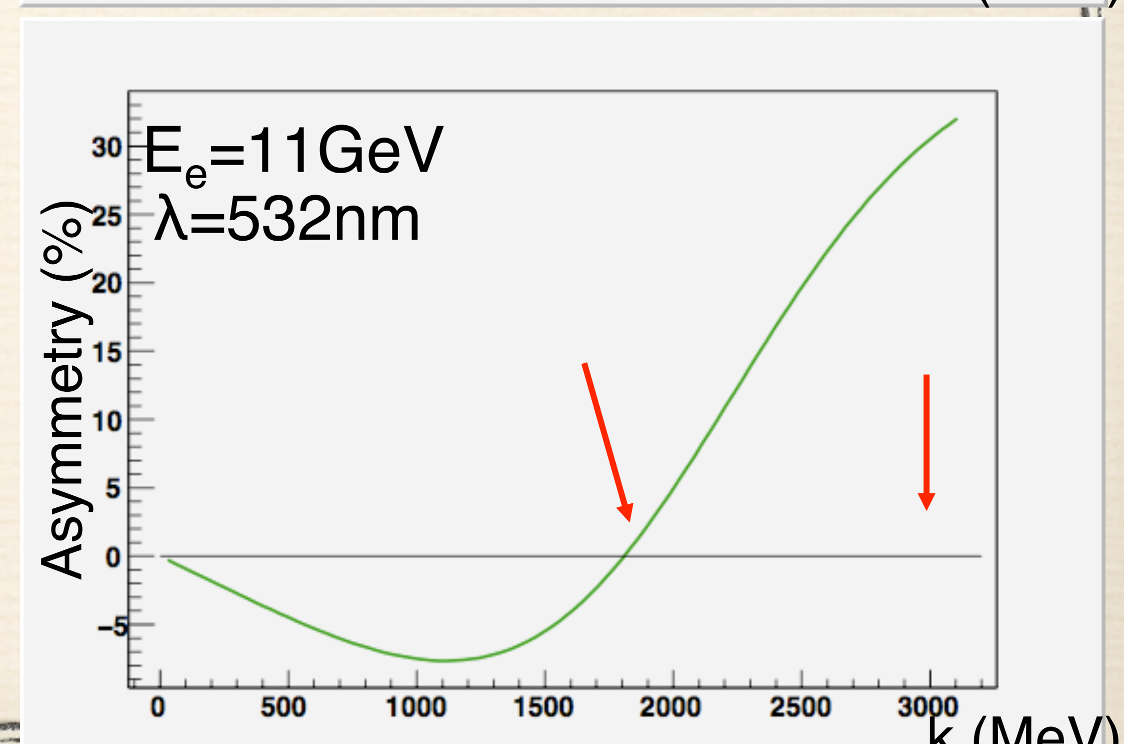


For scattered electrons in chicane:
two Points of well-defined energy!
Asymmetry zero crossing
Compton Edge

Integrate between to minimize error on analyzing power!

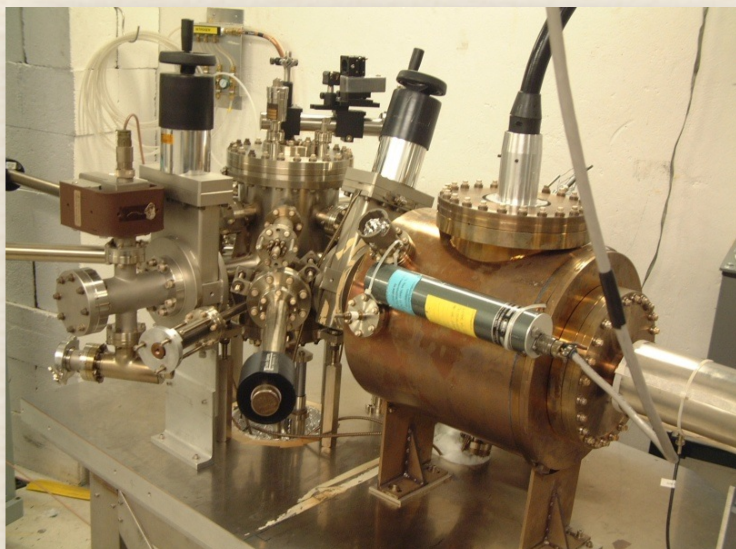
"independent" Photon analysis also normalizable at ~0.5%





Polarized Source at JLab

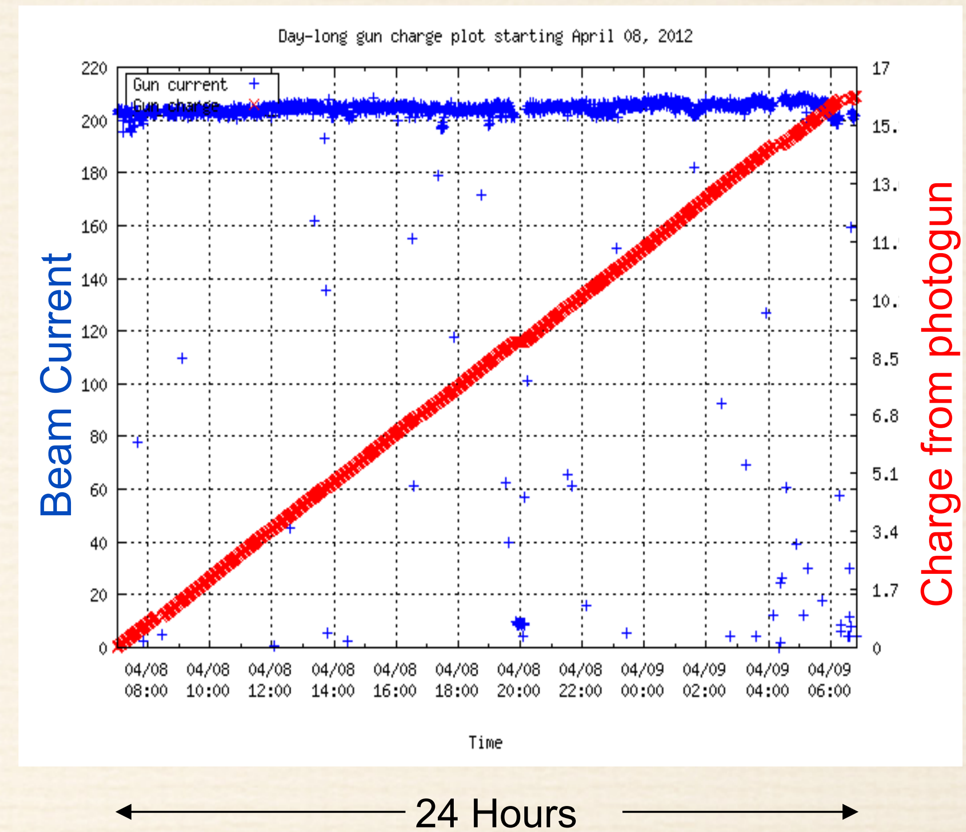
B. Matthew Poelker
2011 E. O. Lawrence Award



Record Performance (2012):
180 μA at 89% polarization

Electron Gun Requirements

- **Ultrahigh vacuum**
- **No field emission**
- **Maintenance-free**



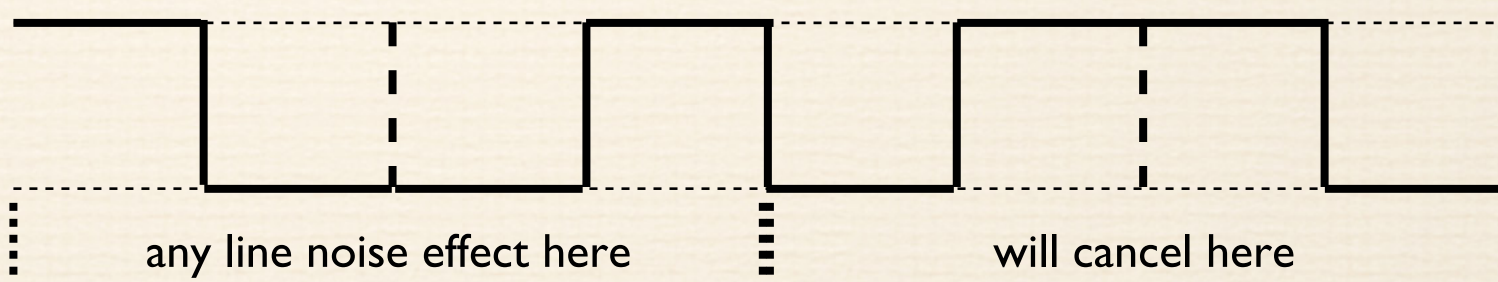
✧ **Beam helicity is chosen pseudo-randomly at multiple of 60 Hz**

- *sequence of "window multiplets"*

Example: at 240 Hz reversal

Choose 2 pairs pseudo-randomly, force complementary two pairs to follow

Analyze each "macropulse" of 8 windows together



MOLLER will plan to use 1.96 kHz reversal; subtleties in details of timing (e.g. 64-plet)

Noise characteristics have been unimportant in past JLab experiments: Not so for PREX, Qweak and MOLLER....

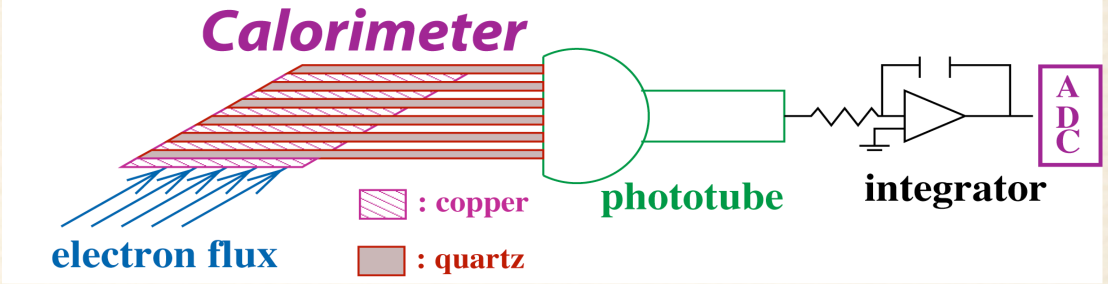
Instantaneous Signal Rate ~ 100 GHz

Flux Integration

1 kHz Pulse Pair Width: ~100 ppm ➡ 10 Billion Pairs: 1 ppb (average 10^7 s)

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

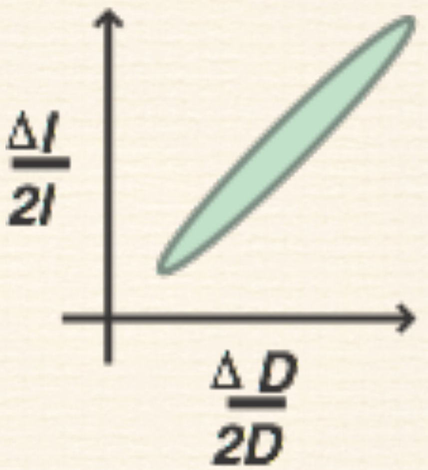
$$A_{pair} = \frac{\Delta F}{2F} + \Delta A$$

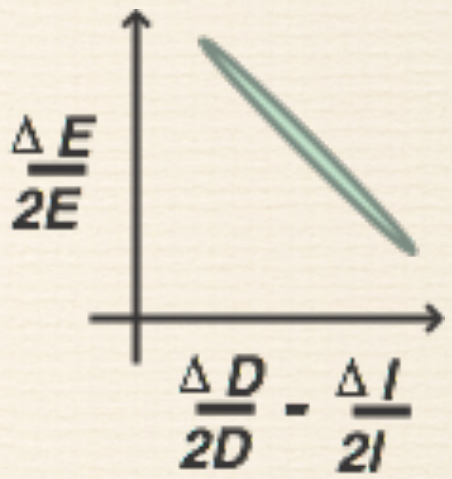


Detector D, Current I: F = D/I

I order: x, y, θ_x, θ_y, E

II order: e.g. spot-size



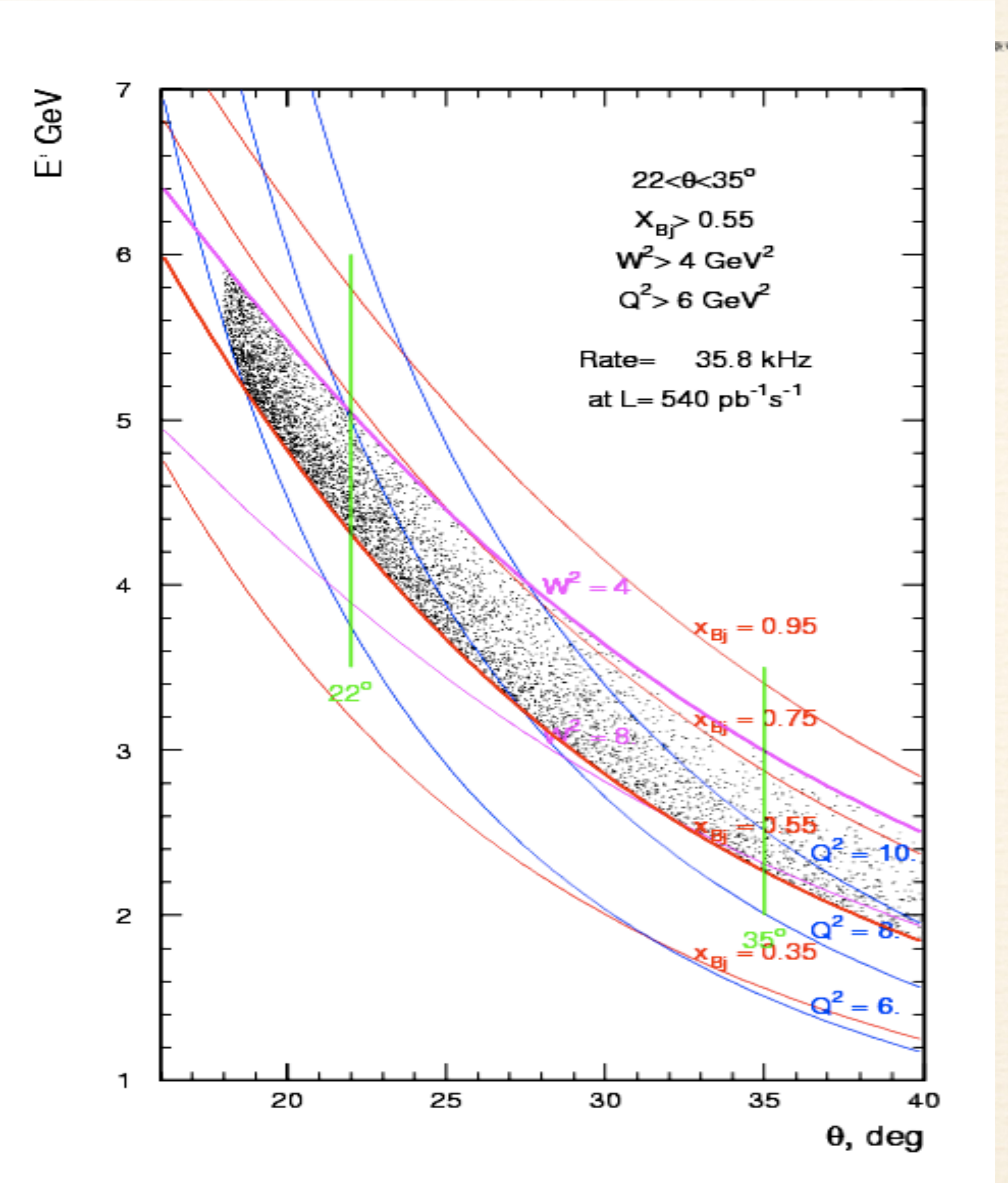


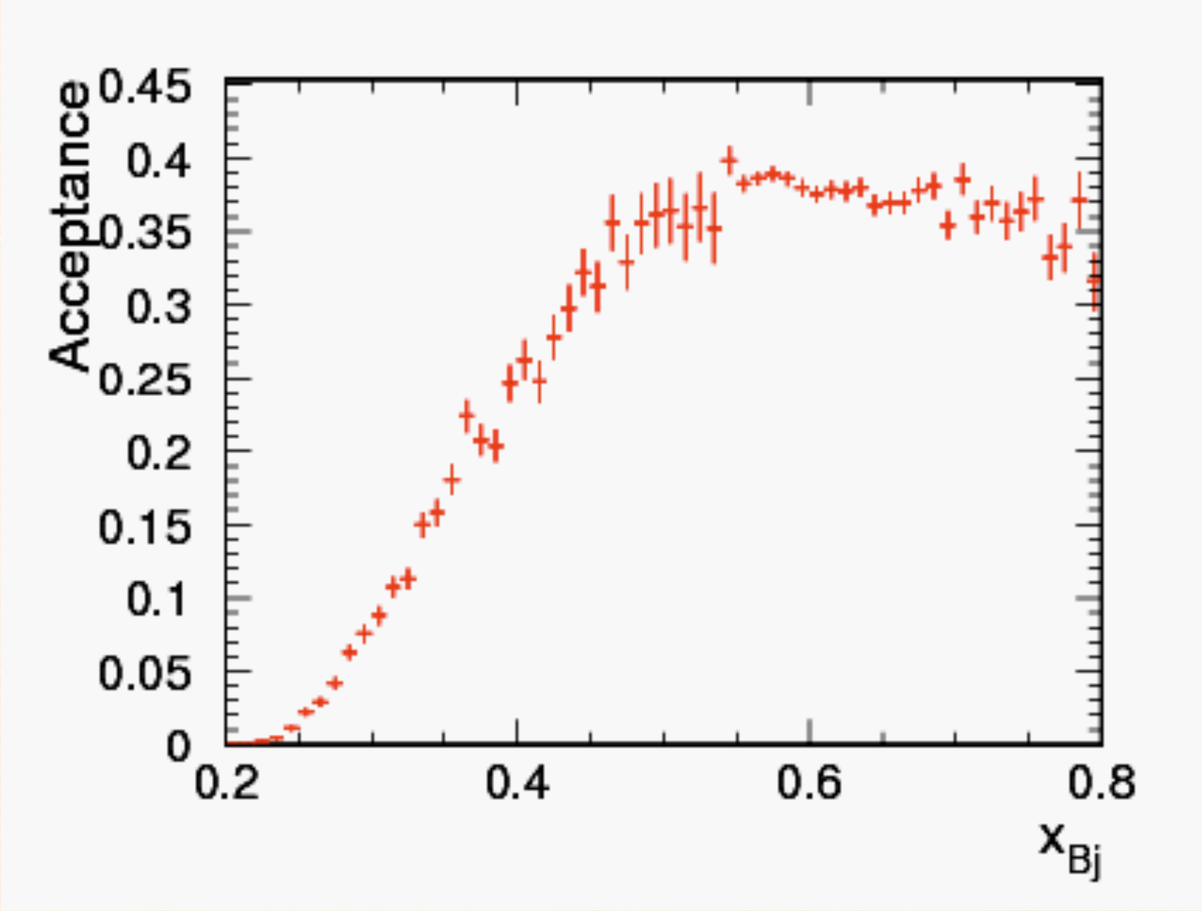
After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 100 ppm (1kHz pairs); central value then reflects A_{phys}

Must minimize (both) random and helicity-correlated fluctuations in average window-pair response of electron beam trajectory, energy and spot-size.

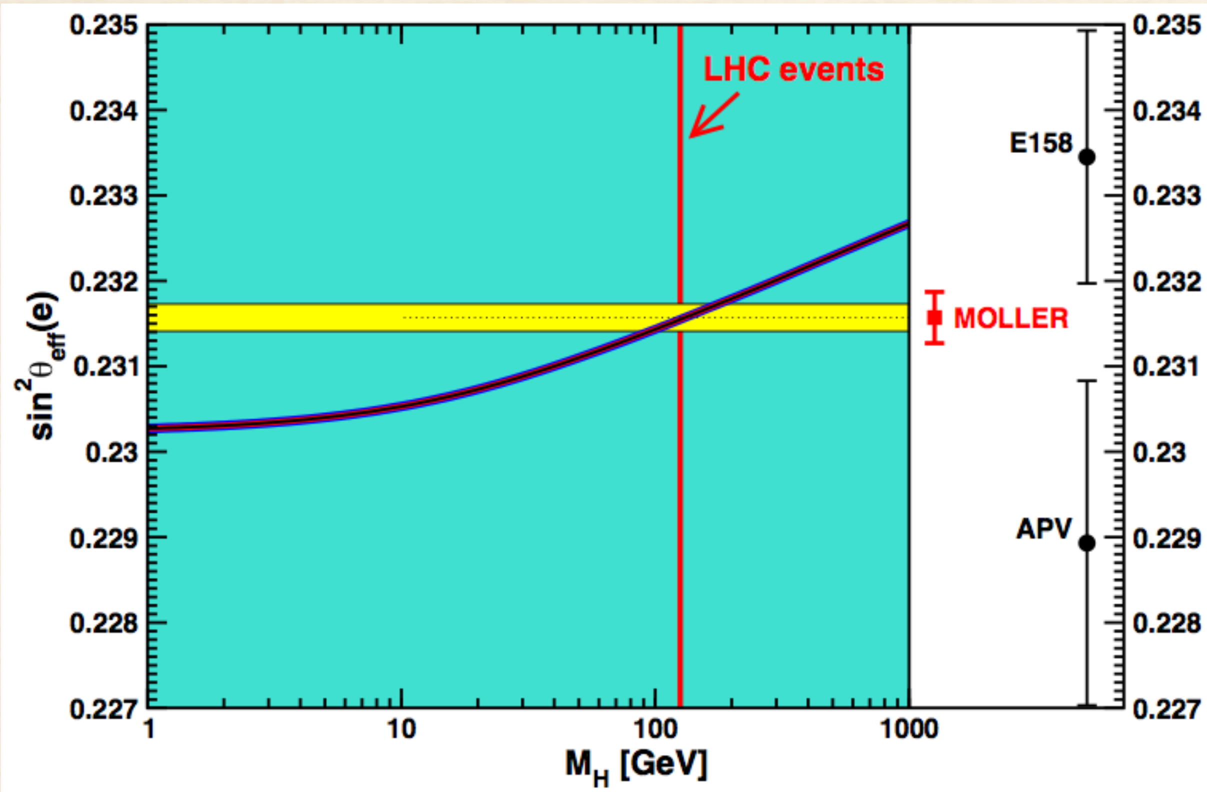
The characteristics of the JLab beam, both at the 2 kHz time scale (~ppm, microns), to grand averages over several days (~ppb, nm), are critical to extracting a measurement which is dominated by statistical fluctuations.

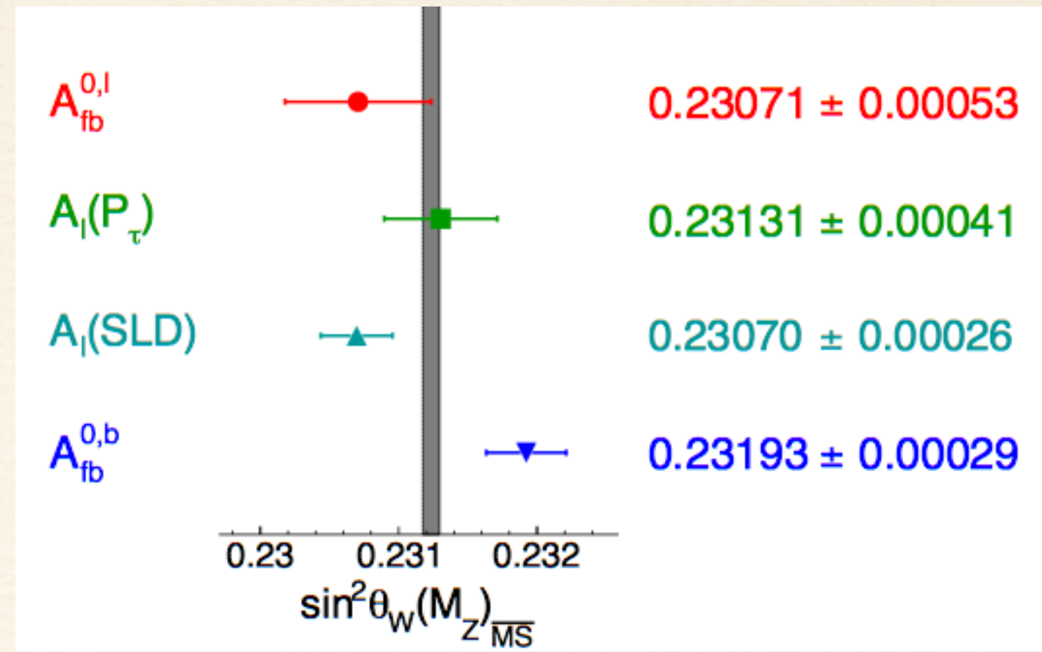
SoLID Acceptance for PVDIS

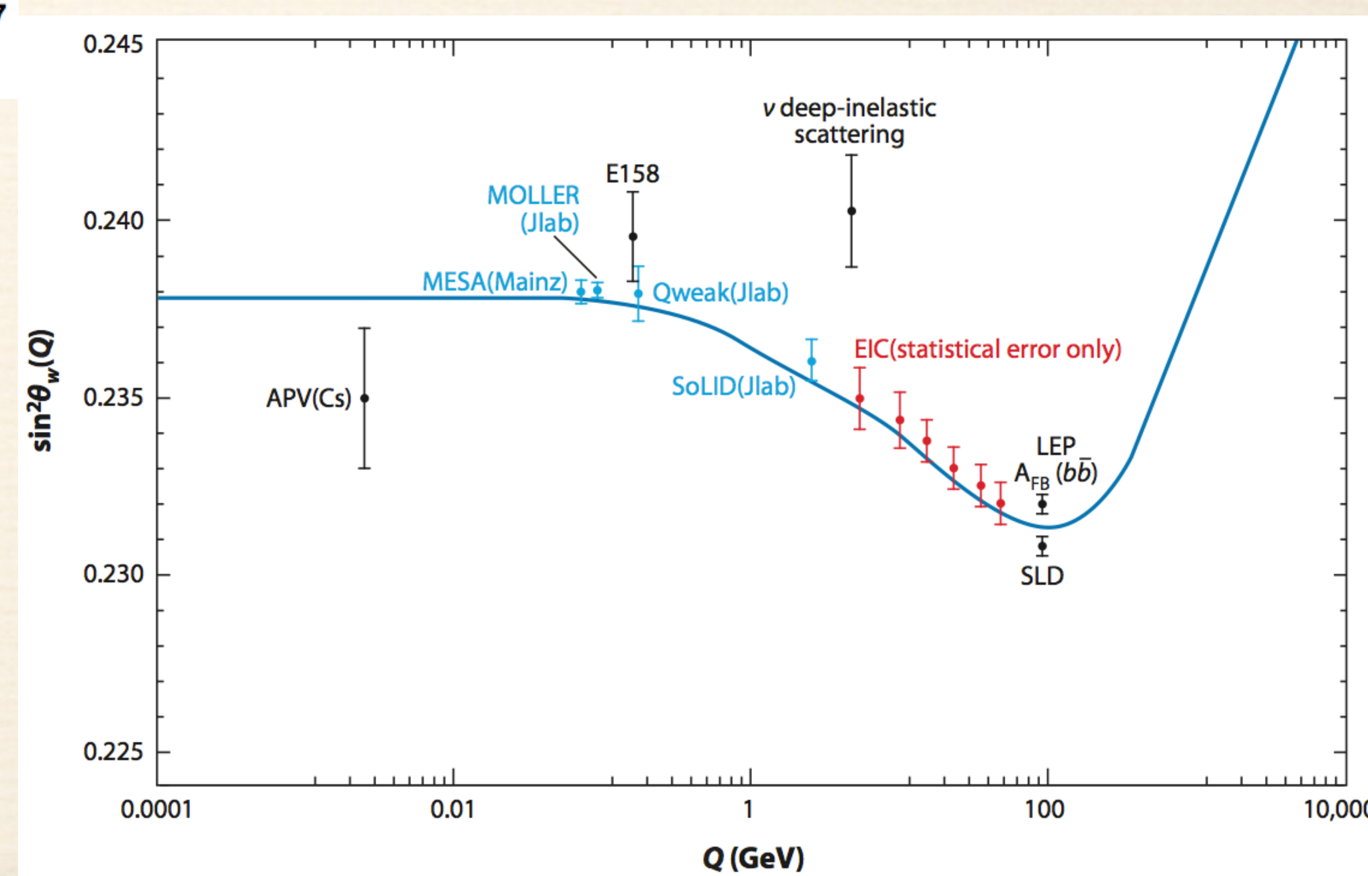




The Higgs and $\sin^2\theta_W$



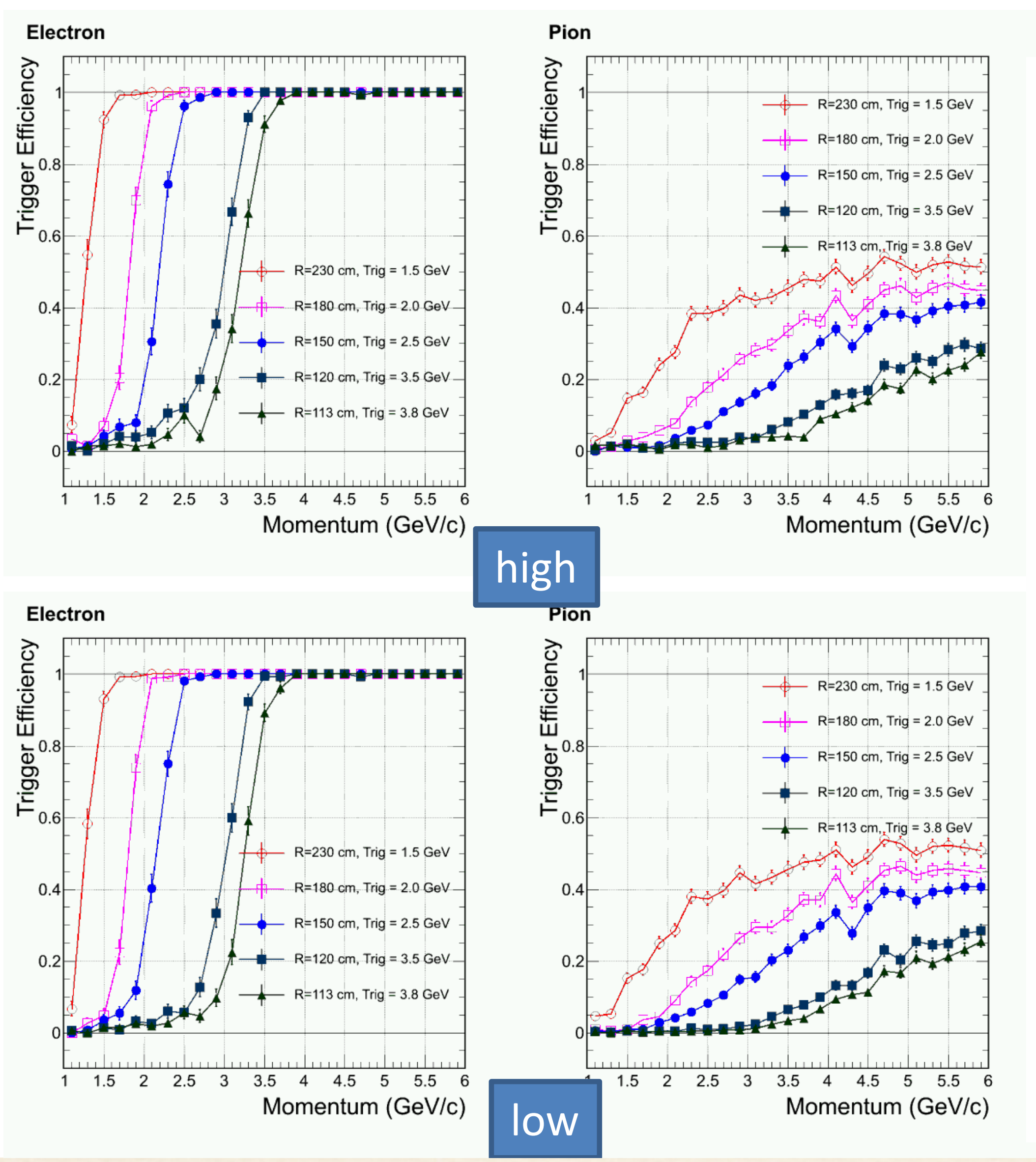


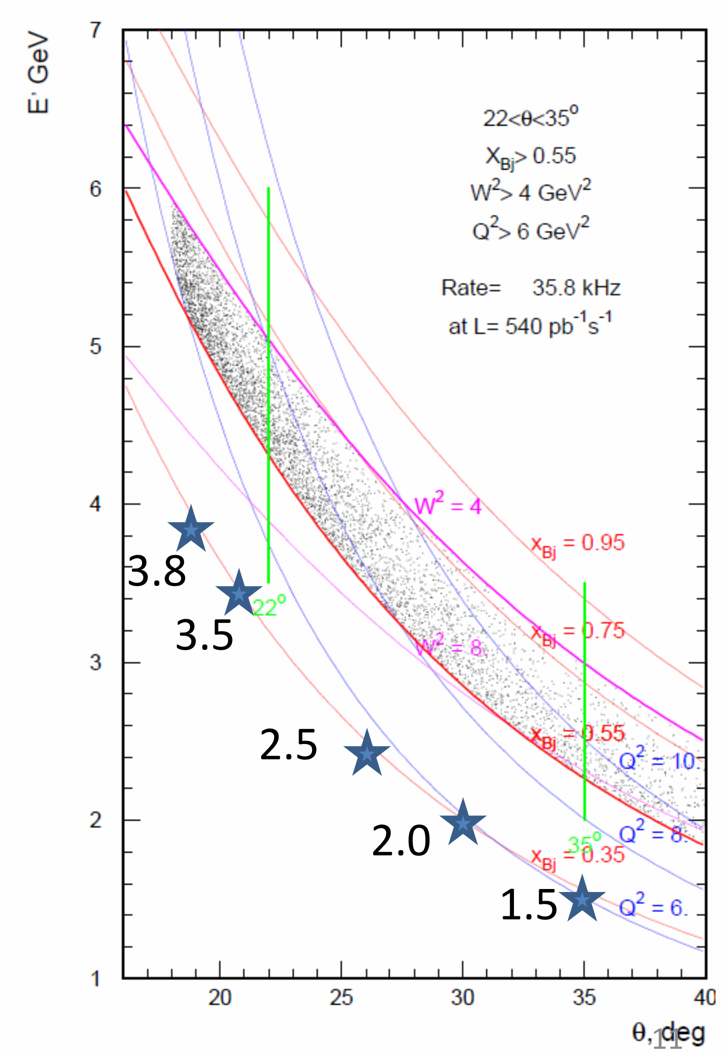


The observation of the Higgs boson and the measurement of its mass has eliminated one of the main uncertainties in precicse predictions of the Standard Model

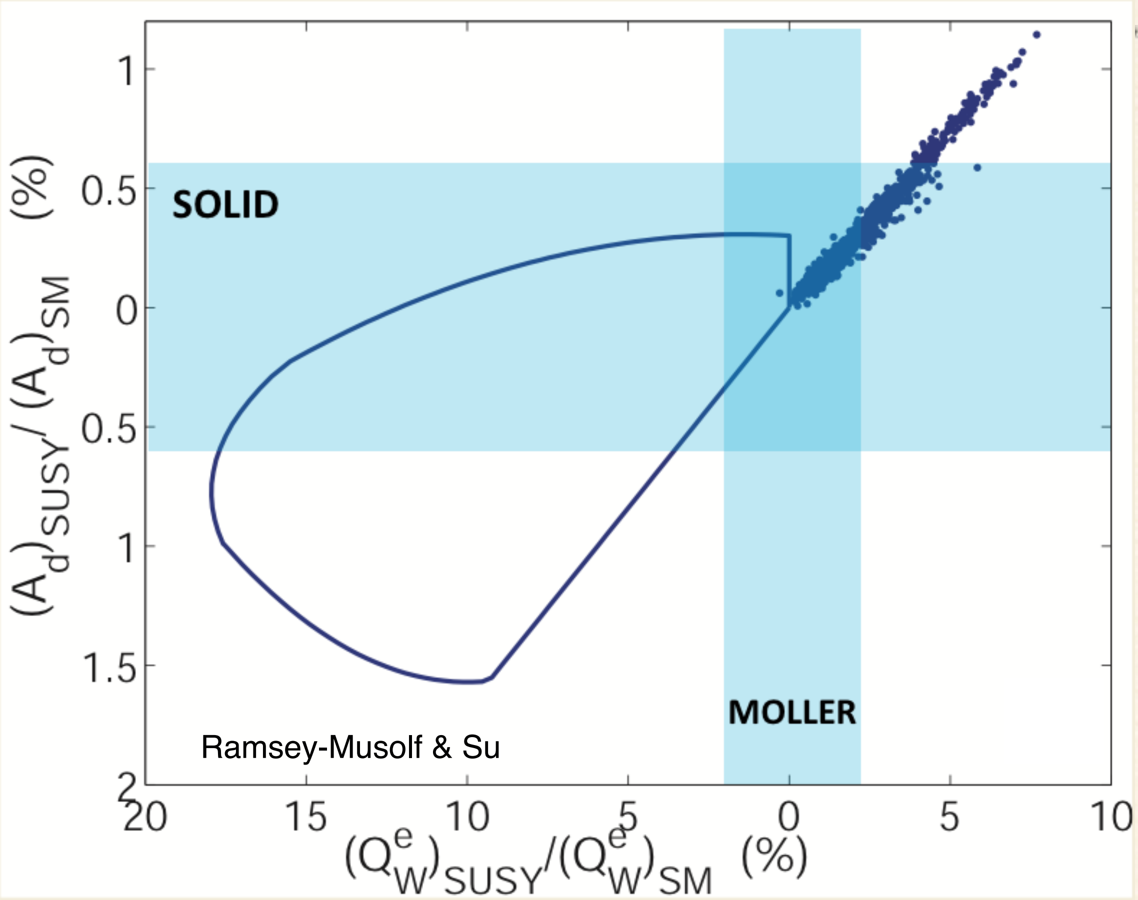
Trigger Issues

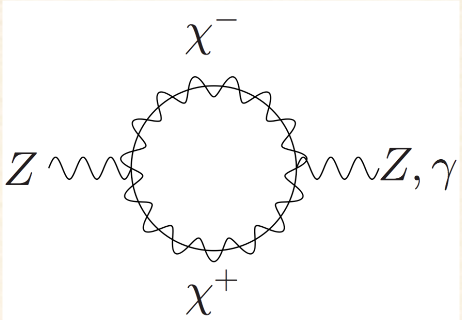
PVDIS FAEC Radius-dependent Trigger





SOLID Sensitivity





Does Supersymmetry provide a candidate for dark matter?

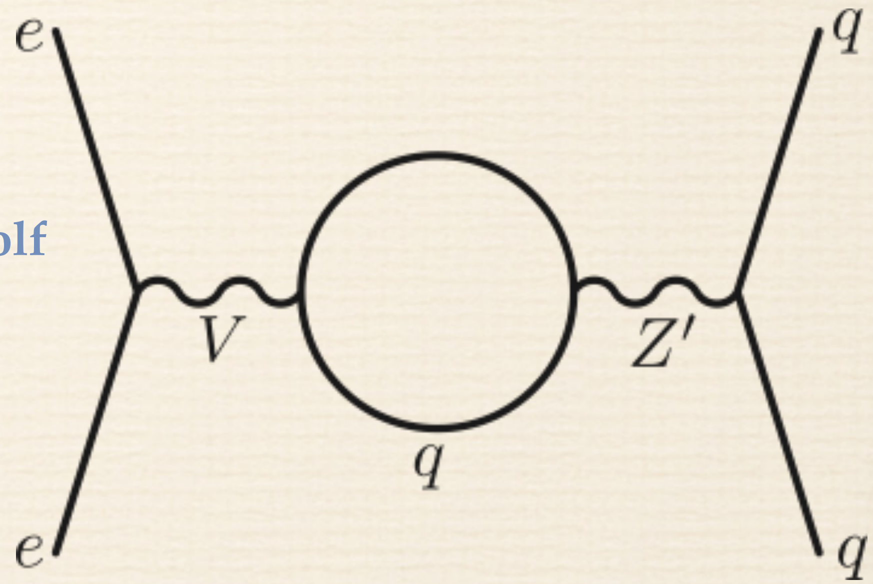
- B and/or L need not be conserved: neutralino decay
- Depending on size and sign of deviation: could lose appeal as a dark matter candidate

Leptophobic Z'

arXiv:1203.1102v1

Buckley and Ramsey-Musolf

- *Virtually all GUT models predict new Z's*
- *LHC reach ~ 5 TeV, but....*
- *Little sensitivity if Z' doesnt couple to leptons*
- *Leptophobic Z' as light as 120 GeV could have escaped detection*



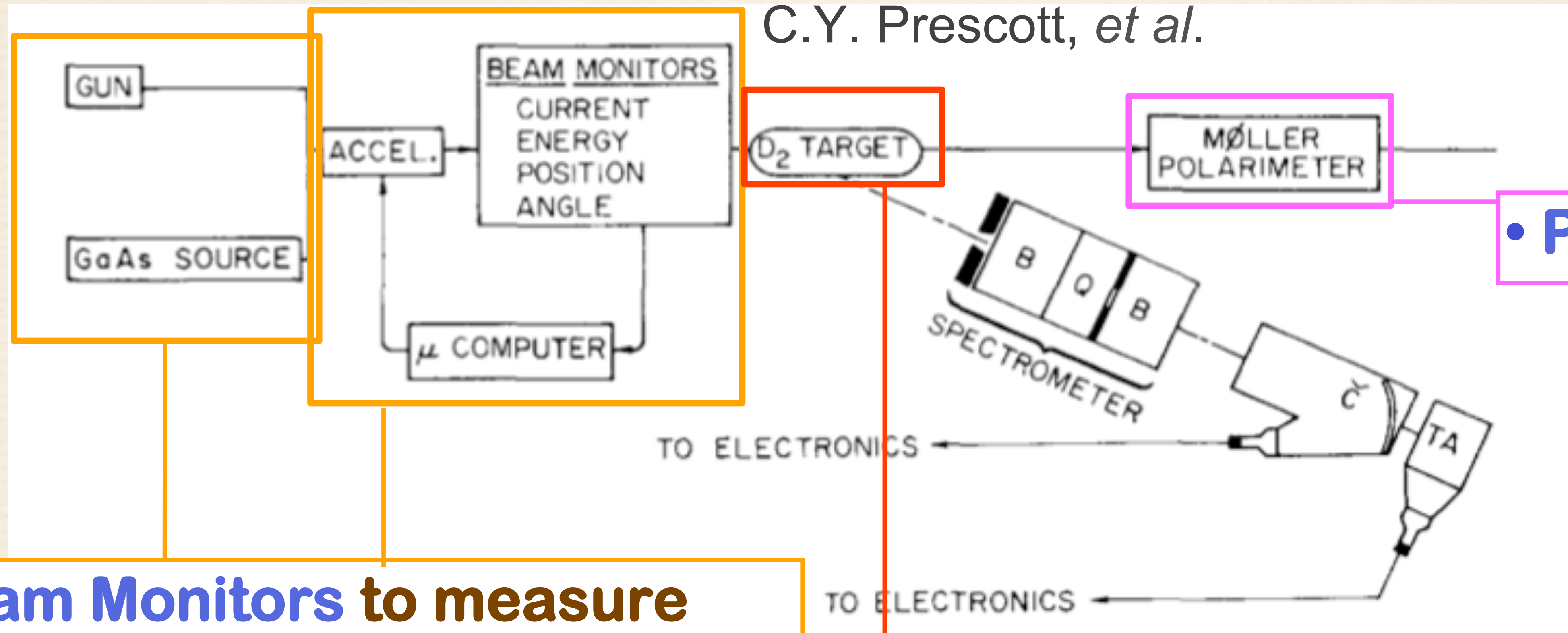
Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect ***C_{2q}'s***

SOLID can improve sensitivity: 100-200 GeV range

Pioneering Design from the mid-70’s; landmark publication in 1978

Schematic Overview

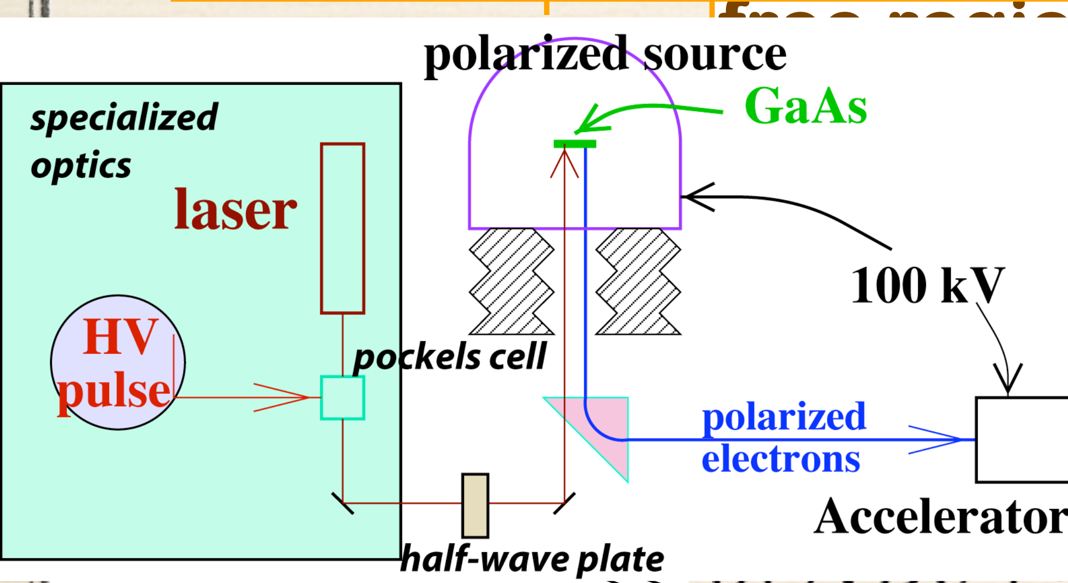
C.Y. Prescott, *et al.*

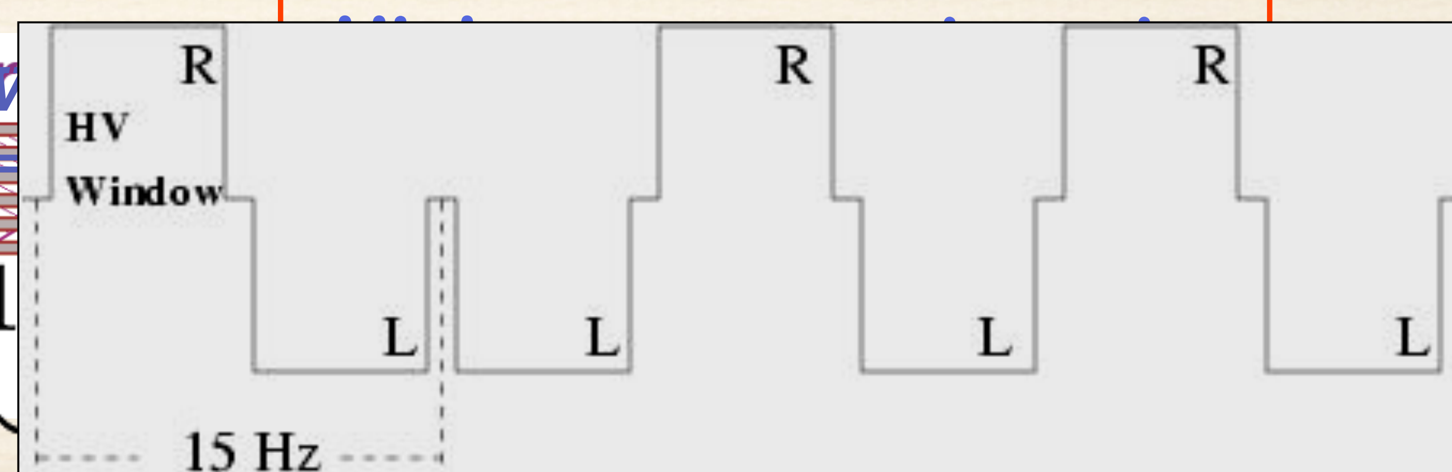


- Polarimetry
- Beam Monitors to measure helicity-correlated changes in beam parameters
- Flux Integration measures high rate without deadtime

✧ Beam helicity sequence is chosen pseudo-randomly

- Helicity state, followed by its complement
- Data analyzed as “pulse-pairs”

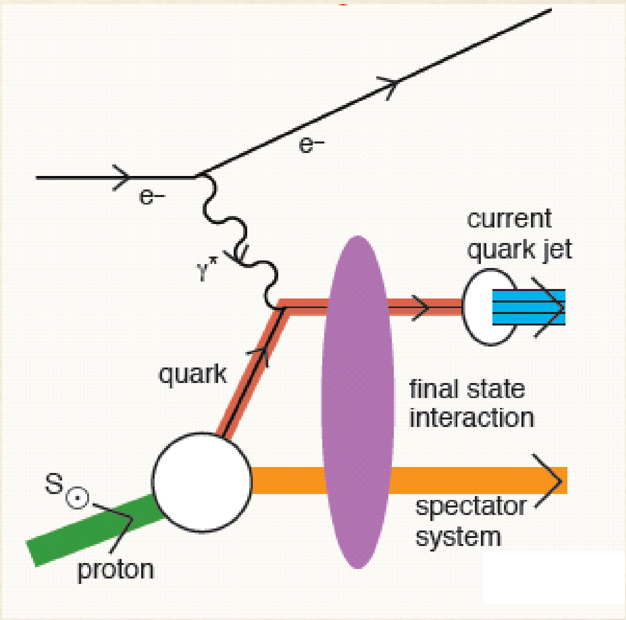




Measurement of TSSA in SIDIS with SoLID on ^{3}He

TMDs are a fundamental property of the nucleon. They provide a 3-D description of nucleon structure in momentum space, and a direct access to QCD dynamics. They involve correlations involving transverse momentum, nucleon spin, and quark spin,

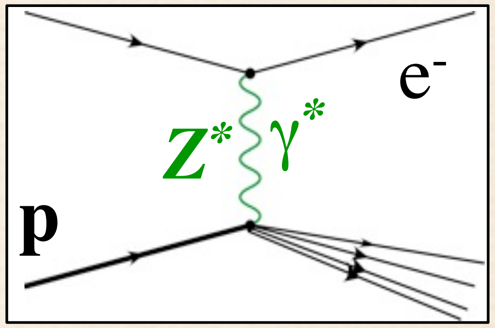
- <10% d quark tensor charge (Collins moments)
  - Fundamental property of nucleon benchmark test of Lattice QCD
- 4-D (x,Q^2,z,P_T) mapping of Sivers moments, etc.
  - Spin-orbital correlation: promising to access Orbital Angular Momentum (OAM)
  - Provide precision data to test TMD factorization and scale evolution



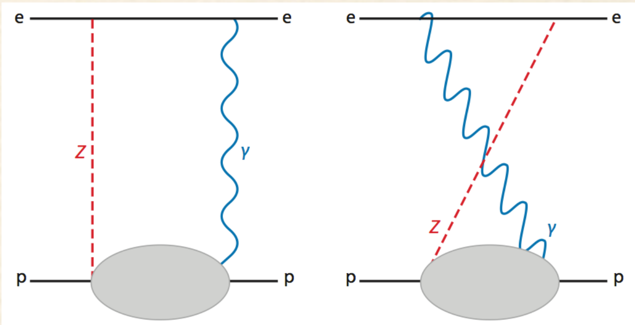
EW Physics and QCD Interplay

- ✦ Strange Quark Form Factors

electrons on LH_2

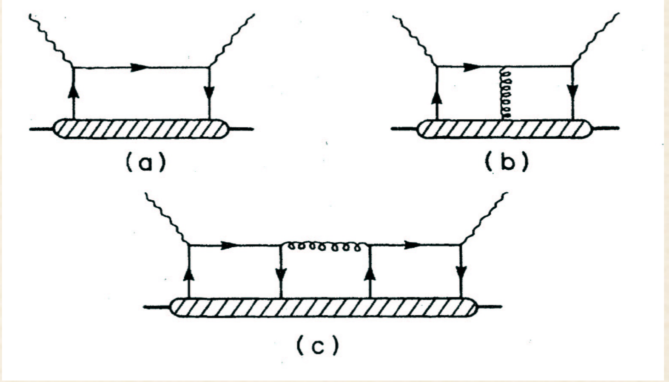


- ✦ Inelastic backgrounds
  - ★ Inelastic e-p scattering in diffractive region (Q^2 <<1 GeV^2, W^2 > 2 GeV^2) pollutes the Møller peak



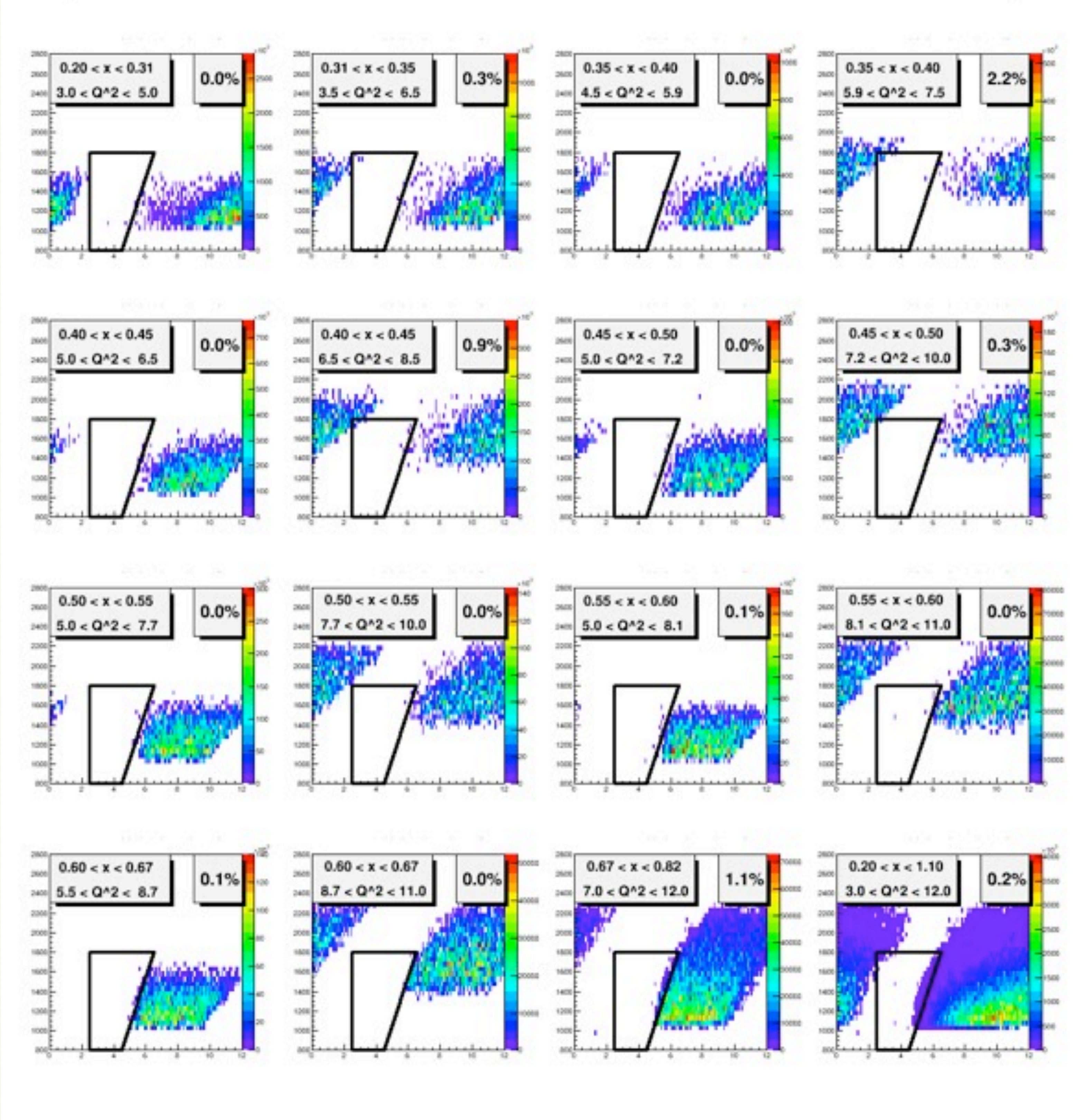
- ✦ Box diagram uncertainties
  - ★ Proton weak charge modified; inelastic intermediate states
- ✦ Parton dynamics in nucleons and nuclei

Physics of SOLID

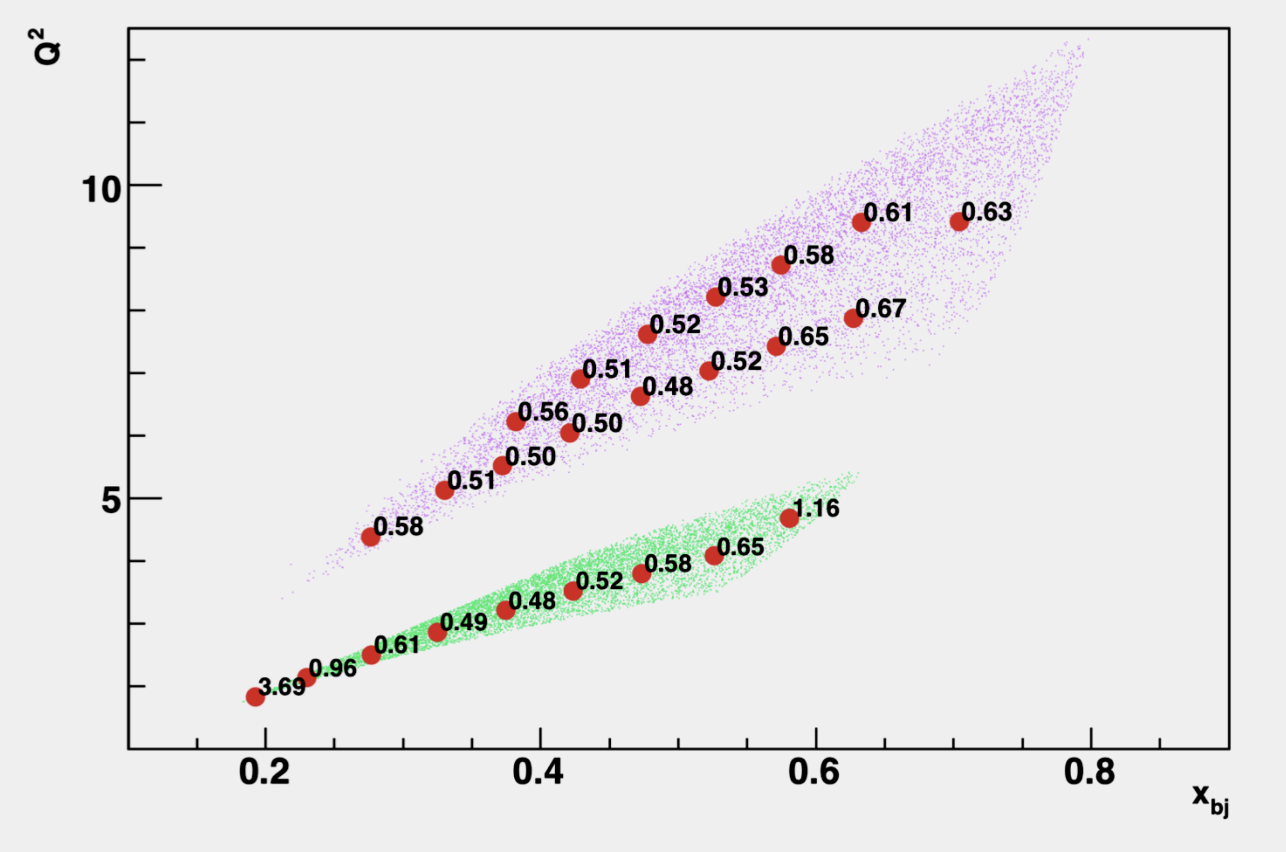


  - ★ Higher twist effects
  - ★ charge symmetry violation in the nucleon
  - ★ "EMC" style effects: quark pdfs modified in nuclei

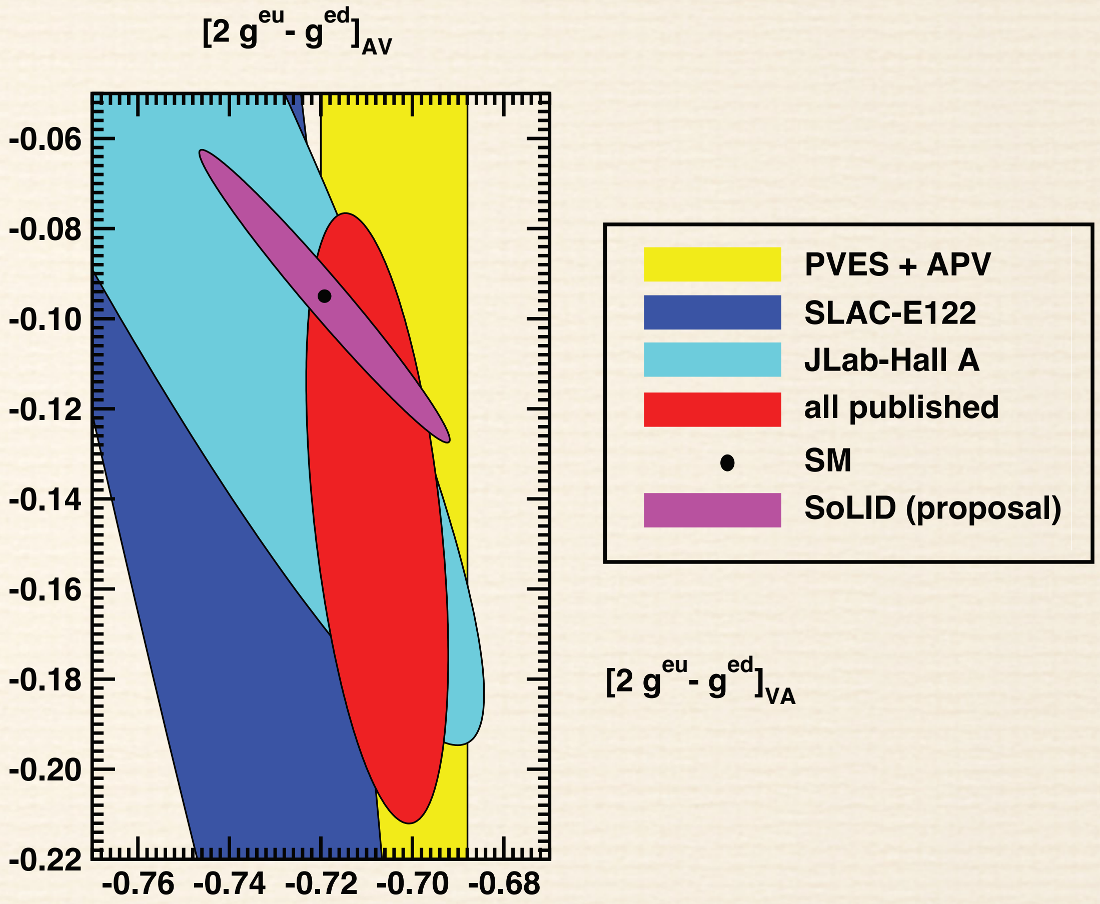
Distribution of DIS Events



Projected PVDIS Data



Asymmetries



Coupling constants

A Special HT Effect

The observation of Higher Twist in PV-DIS would be exciting direct evidence for diquarks

following the approach of
Bjorken, PRD 18, 3239 (78),
Wolfenstein, NPB146, 477 (78)

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

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

Isospin decomposition before using PDF's

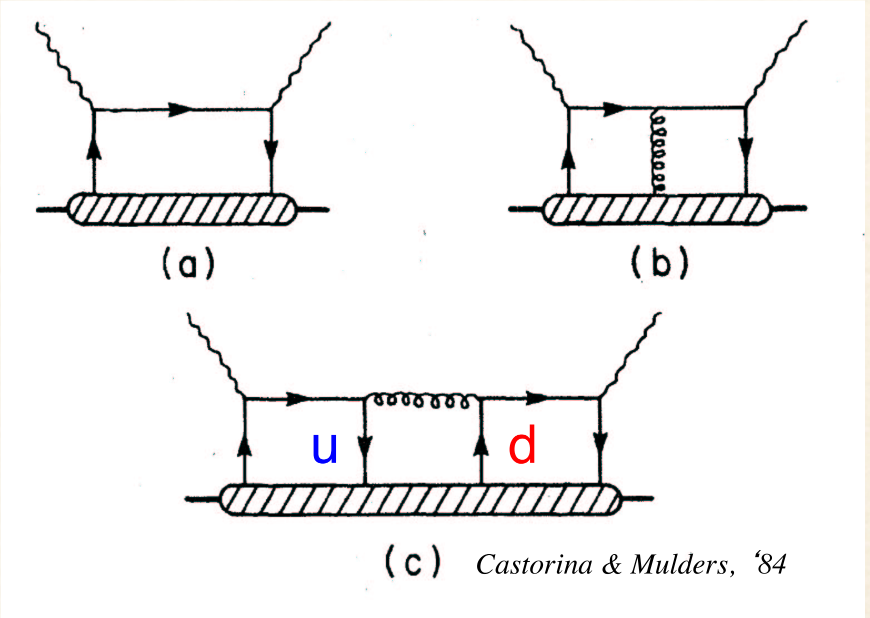
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$\delta = \frac{\langle VV\rangle - \langle SS\rangle}{\langle VV\rangle + \langle SS\rangle} \qquad a(x) \propto \frac{F_1^{\gamma Z}}{F_1^\gamma} \propto 1 - 0.3\delta$$

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

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



(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

σ_L contributions cancel

Use ν data for small b(x) term.

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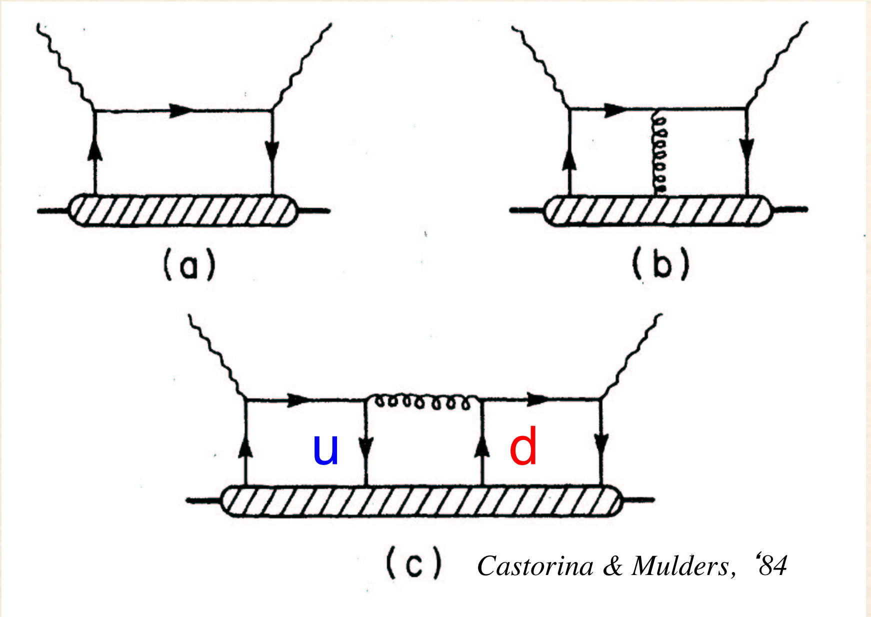


Castorina & Mulders, '84

(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

σ_L contributions cancel

Use ν data for small b(x) term.

Why HT in PVDIS is Special

Bjorken,
PRD 18, 3239 (78)
Wolfenstein,
NPB146, 477 (78)

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

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

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

Isospin decomposition before using PDF's

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

Zero in QPM

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

HT in F_2 may be dominated by quark-gluon correlations

Higher-Twist valance quark-quark correlations

Vector-hadronic piece only

Use ν data for small b(x) term.

A number of calculations (bag model, …) predict negligible effects.

QCD: Charge Symmetry Violation

$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

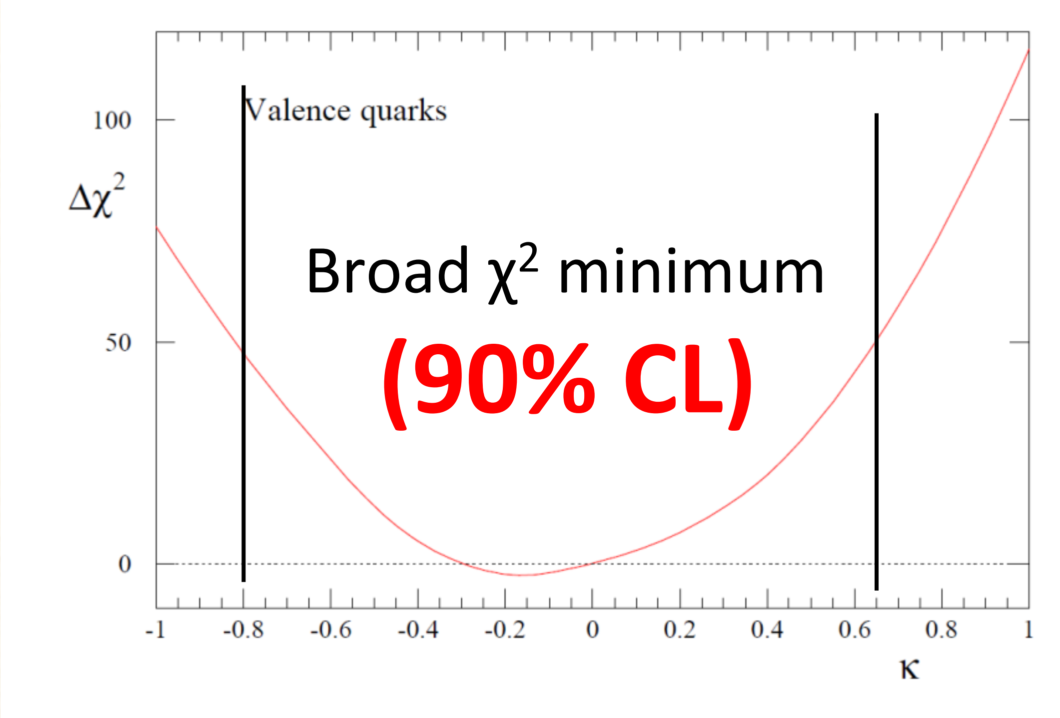
$$\frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

We already know CSV exists:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV

  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

MRST PDF global with fit of CSV
Martin, Roberts, Stirling, Thorne Eur Phys J C**35**, 325 (04)



QCD: Higher Twist--MRST Fits

$F_2(x,Q^2)=F_2(x)(1+D(x)/Q^2)$

$Q^2=(W^2-M^2)/(1/x-1)$

$Q^2_{min}=Q^2(W=2)$

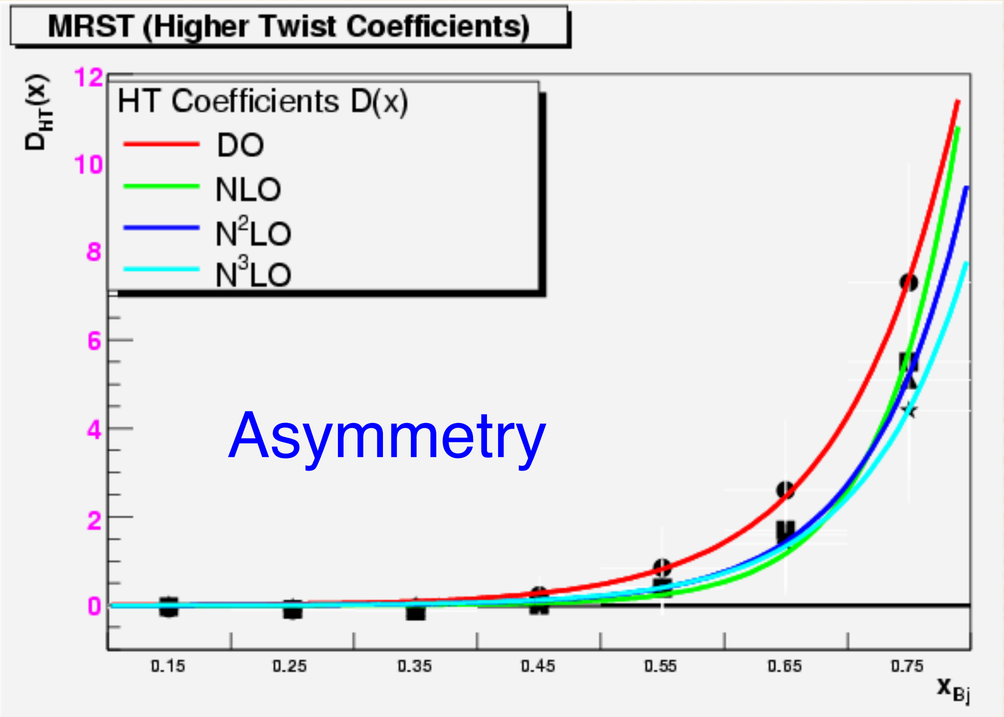
MRST, PLB582, 222 (04)

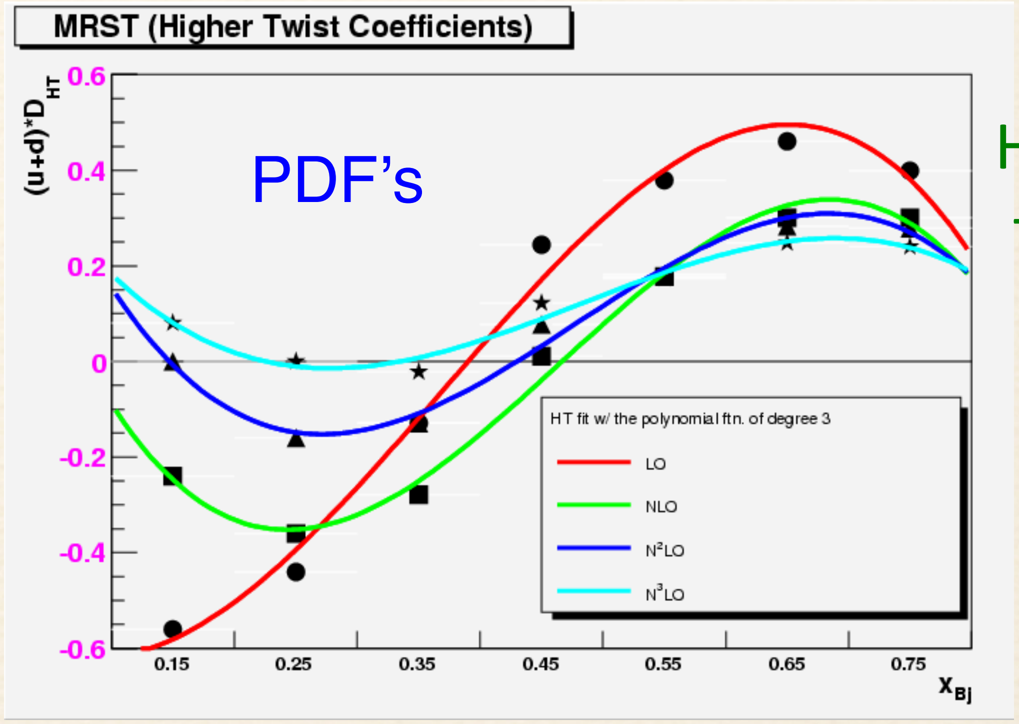
x	Q^2_{min}	D(x)		D/Q^2_{min} (%)	
		LO	N^3LO	LO	N^3LO
0.1-0.2	0.5	-.007	0.001	-14	2
0.2-0.3	1.0	-.11	0.003	-11	0.0
0.3-0.4	1.7	-.06	-0.001	-3.5	-0.5
0.4-0.5	2.6	.22	0.11	8	4
0.5-0.6	3.8	.85	0.39	22	10
0.6-0.7	5.8	2.6	1.4	45	24
0.7-0.8	9.4	7.3	4.4	78	47

$$A_{\mathrm{meas.}} = A_{\mathrm{PV}}\left[1+\frac{C(x)}{Q^2}\right]$$

If C(x)~D(x), there is large sensitivity al large x.

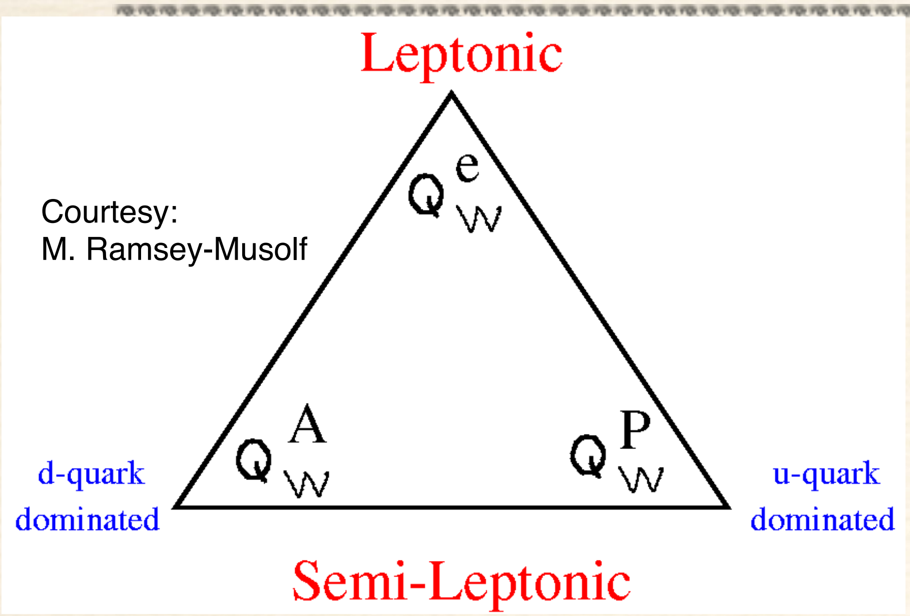
Order of DGLAP influences size of HT





Higher twist falls slowly compared to PDF's at large x.

PVES Initiatives: Complementarity



vector-quark couplings

$$[2C_{2u} - C_{2d}]$$

axial-quark couplings

SUSY Loops → Q_W^e and Q_W^p:same absolute shift, smaller for others

GUT Z' → High for Q_W(Cs), Q_W^e(relative), smaller for others

Leptophobic Z' → axial-quark couplings (C_2's) only

RPV SUSY → Different for all four in sign and magnitude

Leptoquarks → semi-leptonic only; different sensitivities

Lepton Number Violation → Q_W^e only