The Physics Case for PVDIS with SoLID

and lepton pair production at the LHC

P. A. Souder

Outline

- The solid spectrometer and experimental program
- BSM Physics and PVDIS
- Implications of LHC Data
- PVES as a probe of hadronic structure (and BSM physics)

Overview of SoLID in Hall A

Solenoidal Large Intensity Device

- Full exploitation of JLab 12 GeV Upgrade

  → A Large Acceptance Detector AND Can Handle High Luminosity (10^{37}-10^{39})

  Take advantage of latest development in detectors , data acquisitions and simulations

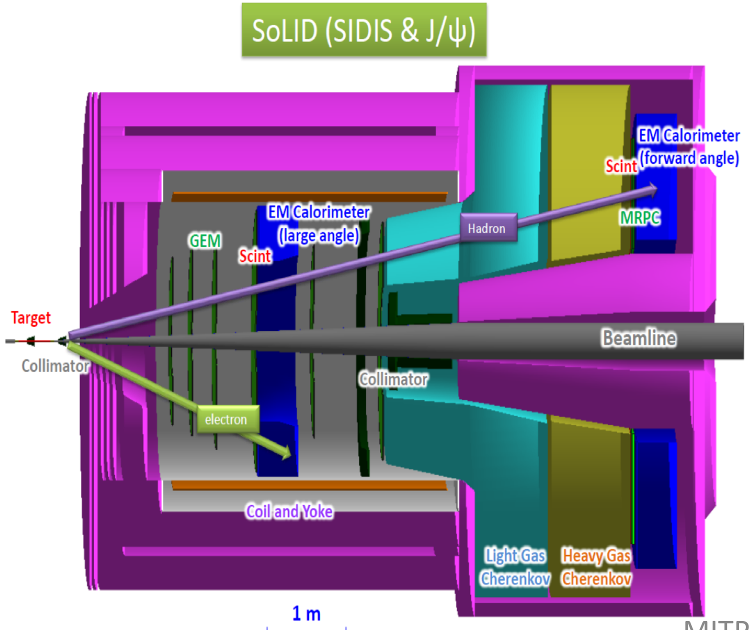
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-x region and threshold J/ψ

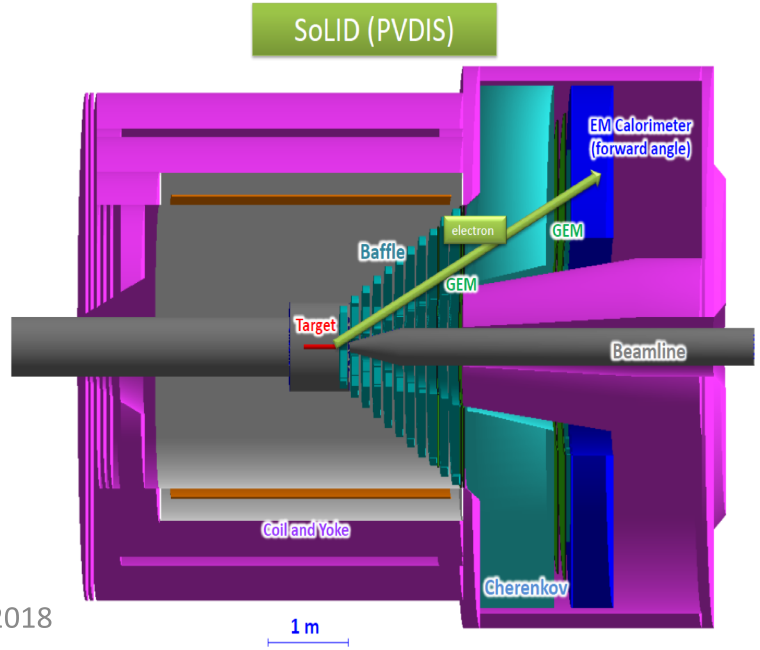
- 5 highly rated experiments approved

  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 3 run group experiments)

- Strong collaboration (250+ collaborators from 70+ institutes, 13 countries)

  Significant international contributions (Chinese collaboration)





SoLID Timeline

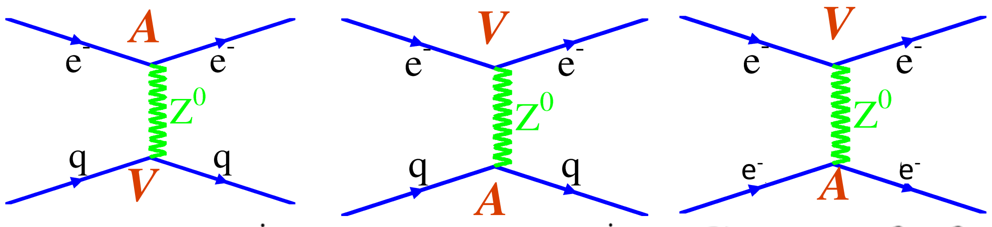
- 2017 Passed Director's Review
- 2018 DOE Science review
  - Must have updated Physics case
- 2020 CD0
- 2025 Construction finished??

Non-PVDIS Physics Case: An Enhanced Science Impact of SoLID through the NAS report lens

- NAS report soon to be released. Two science questions have taken center stage are:
  - What is the origin of mass?
    - SoLID will contributes to answering this question with a “precision measurement of the J/psi cross section in photo-production very close to threshold. This physics is best done at high luminosity i.e. with SoLID because of the rapid decrease of the production cross section at threshold. The goal is to access of the trace anomaly (pure gluonic contribution) to the mass of the nucleon. This quantity, that give mass to the nucleon even when the quark masses are zero (chiral limit) is a fundamental consequence of scale invariance in QCD.

    - The EIC cannot access the J/Psi threshold region, however, it will use the Upsilon (heavier) production at threshold to measure the same quantity. We expect this complementary measurement to be important and should confirm JLab’s extraction of the trace anomaly.
  - What is the origin of Spin?
    - The SoLID Transverse Momentum Distributions program with its momentum imaging goal of the using SoLID is the precursor and stepping platform for the EIC imaging program.
    - While JLab will provide for exquisite momentum imaging of both the proton and the neutron enabling a flavor decomposition in the valence quark region the EIC will benefit from the overlap x region and will focus on the sea-quark dominated region and gluons.

PVES and Contact Interactions

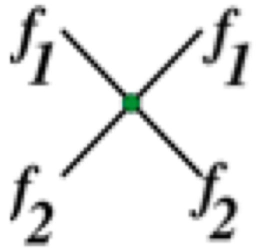


$C_{1i} \equiv 2g_A^e g_V^i$ $\quad C_{2i} \equiv 2g_V^e g_A^i$ $\quad C_{ee} = 2g_V^e g_A^e$

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

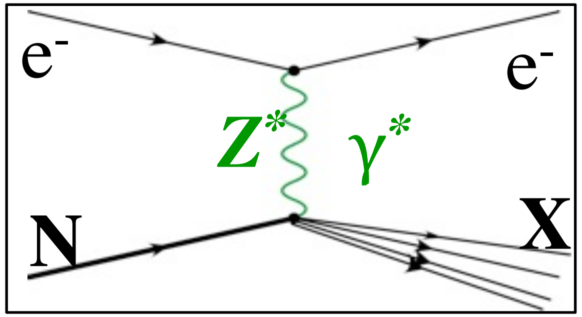
$$\begin{aligned} C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W &\approx& -0.19 \\ C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W &\approx& 0.35 \\ C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W &\approx& -0.04 \\ C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W &\approx& 0.04 \\ C_{ee} &= \frac{1}{2}-2\sin^2\theta_W &\approx& 0.02 \end{aligned}$$

+ new physics



$$\mathcal{L}_{eff}^{BSM} = \frac{g^2}{\Lambda^2}\sum_{i,j=L,R}\eta_{ij}^{eff}\bar{e}_i\gamma_\mu e_i\bar{q}_j\gamma^\mu q_j$$
$$= g^2\sum_{i,j=L,R}\left(\frac{1}{\Lambda_{ij}^{ef}}\right)^2\bar{e}_i\gamma_\mu e_i\bar{f}_j\gamma^\mu f_j$$

Theory of PVDIS



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

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

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

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

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

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

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

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

Published 6 GeV PVDIS data from JLab

6 GeV run results

Q^2 ~ 1.1 GeV^2

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

Q^2 ~ 1.9 GeV^2

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

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

PARTICLE PHYSICS

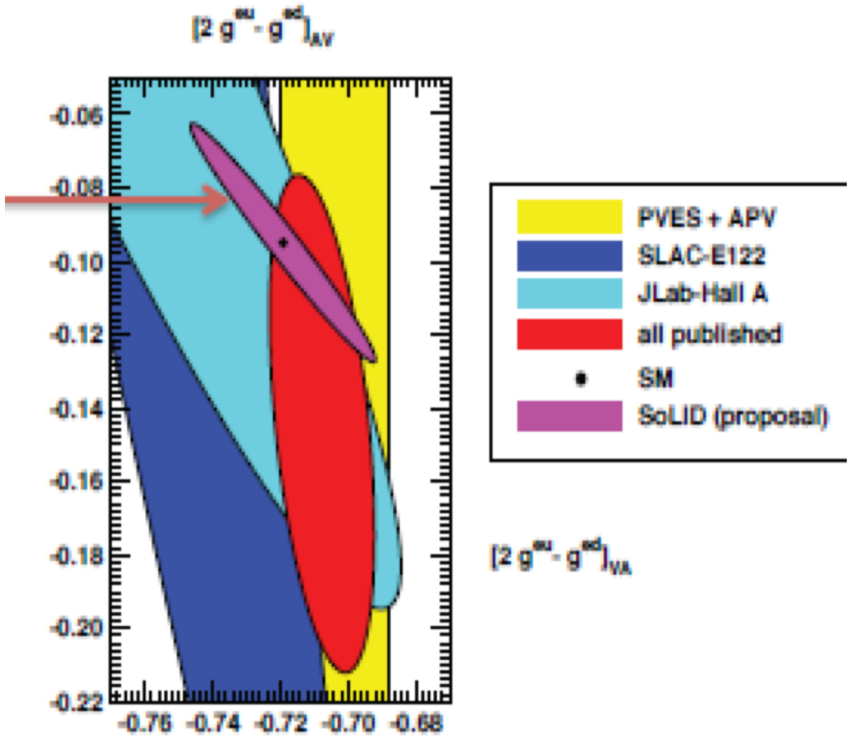
Quarks are not ambidextrous

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

W. Marciano article in Nature

SoLID and the Low Energy PVES Program

- Measure each of the coupling constants as precisely as possible.
- The C_2's are the most difficult to measure.
  - Large, uncalculable radiative corrections present in coherent processes.
- PVDIS is the most promising approach to measure one combination for the the C_2's.



What Does the LHC Say?

- $PP \to l^+ l^-$ data are relevant
- LHC data is interpreted in terms of the Λ_{LR}

Relating $\Delta C's$ to $\Lambda's$

$\eta_{ij}/\Lambda \rightarrow 1/\Lambda_{LR} \rightarrow 1/\Lambda_{VA} \rightarrow \Delta C$

Constants related by 4X4 matrices

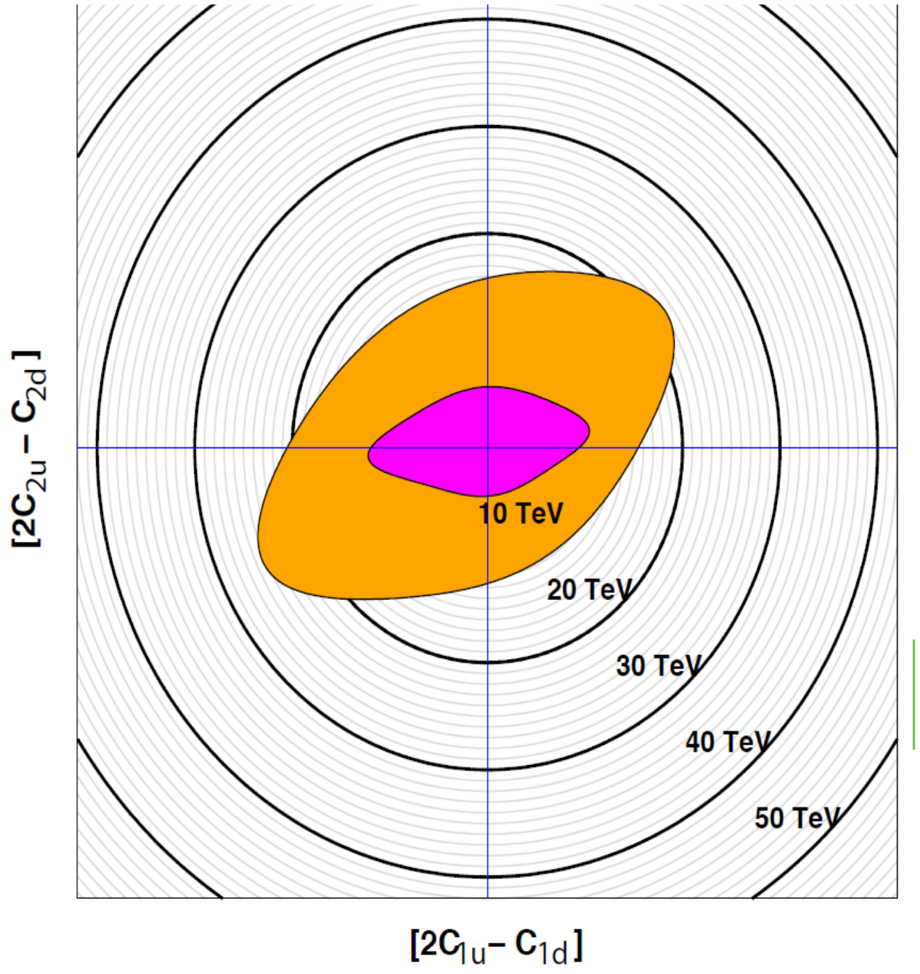
$$4\bar{e}_R\gamma_\mu e_R\bar{q}_R\gamma^\mu q_R = \{\bar{e}\gamma_\mu e\}\{\bar{q}\gamma^\mu q\} + \{\bar{e}\gamma_\mu\gamma^5 e\}\{\bar{q}\gamma^\mu q\} + \{\bar{e}\gamma_\mu e\}\{\bar{q}\gamma^\mu\gamma^5 q\} + \{\bar{e}\gamma_\mu\gamma^5 e\}\{\bar{q}\gamma^\mu\gamma^5 q\}$$

$$\mathcal{L}_{eff}^{BSM} = g^2\Bigg[\left(\frac{1}{\Lambda_{VV}^{eq}}\right)^2\{\bar{e}\gamma_\mu e\}\{\bar{q}\gamma^\mu q\} + \left(\frac{1}{\Lambda_{AV}^{eq}}\right)^2\{\bar{e}\gamma_\mu\gamma^5 e\}\{\bar{q}\gamma^\mu q\} + \left(\frac{1}{\Lambda_{VA}^{eq}}\right)^2\{\bar{e}\gamma_\mu e\}\{\bar{q}\gamma^\mu\gamma^5 q\} + \left(\frac{1}{\Lambda_{AA}^{eq}}\right)^2\{\bar{e}\gamma_\mu\gamma^5 e\}\{\bar{q}\gamma^\mu\gamma^5 q\}\Bigg]$$

Sensitivity in terms of Λ

Sensitive to very large values of Λ, competitive with with LHC data?

Oval: SoLID + Qweak



Lepton Pair Production form ATLAS

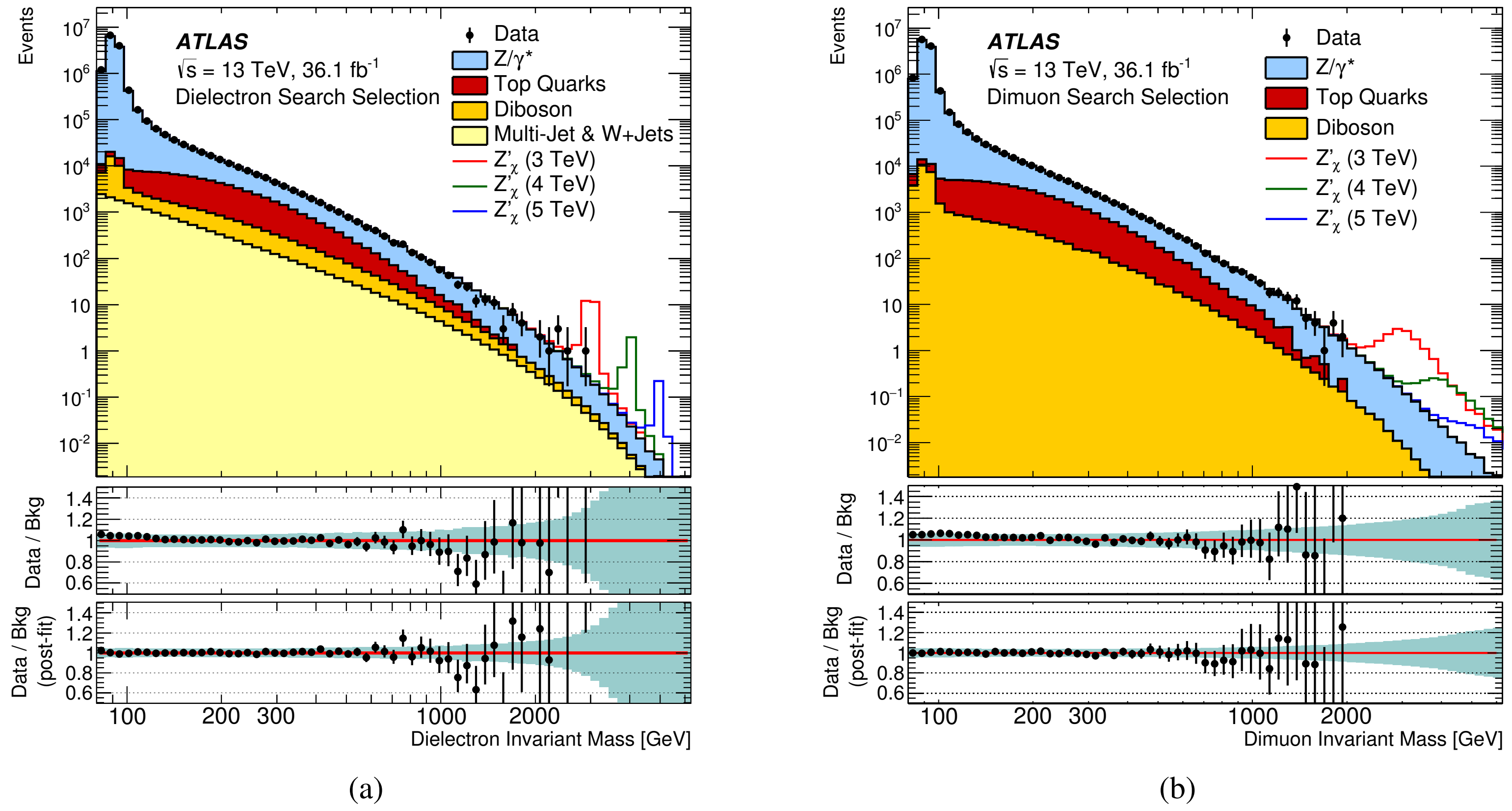


Figure 1: Distributions of (a) dielectron and (b) dimuon reconstructed invariant mass ($m_{\ell\ell}$) after selection, for data and the SM background estimates as well as their ratio before and after marginalisation. Selected Z'_χ signals with a pole mass of 3, 4 and 5 TeV are overlaid. The bin width of the distributions is constant in $\log(m_{\ell\ell})$ and the shaded band in the lower panels illustrates the total systematic uncertainty, as explained in Section 7. The data points are shown together with their statistical uncertainty.

Features of LHC Data

- Data goes up to 2 TeV!
- Lots of statistics at low s
- Errors at low s dominated by PDF uncertainties
- Conclusion I: Contact interaction analysis valid only for $\Lambda \gg 2$ TeV.
- Conclusion II: Need g2=4π

Lepton Pair Production Cross Sections

$$\frac{d\sigma}{d\Omega}(q_L\bar{q}_R \to e_L^- e_R^+) = \frac{\alpha^2}{4s}(1+\cos\theta)^2 \left| Q_q - rL_qL_e - \frac{s}{\alpha(\Lambda_{LL}^{eq})^2} \right|^2$$

$$\frac{d\sigma}{d\Omega}(q_L\bar{q}_L \to e_L^- e_L^+) = \frac{\alpha^2}{4s}(1-\cos\theta)^2 \left| Q_q - rL_qR_e - \frac{s}{\alpha(\Lambda_{LR}^{eq})^2} \right|^2$$

$$\frac{d\sigma}{d\Omega}(q_R\bar{q}_L \to e_R^- e_L^+) = \frac{\alpha^2}{4s}(1+\cos\theta)^2 \left| Q_q - rR_qR_e - \frac{s}{\alpha(\Lambda_{RR}^{eq})^2} \right|^2$$

$$\frac{d\sigma}{d\Omega}(q_R\bar{q}_R \to e_R^- e_R^+) = \frac{\alpha^2}{4s}(1-\cos\theta)^2 \left| Q_q - rR_qL_e - \frac{s}{\alpha(\Lambda_{RL}^{eq})^2} \right|^2$$

Two Types of Terms

1. Interference ~ $1/\Lambda^2$
2. Direct Terms ~ $1/\Lambda^4$

Since LHC is unpolarized,
It measures the sum of all
Four cross sections

Direct Terms Set Limits on PV Couplings

Direct terms in cross Section measure:

$$\left(\frac{1}{\Lambda^{eq}_{LL}}\right)^4 + \left(\frac{1}{\Lambda^{eq}_{LR}}\right)^4 + \left(\frac{1}{\Lambda^{eq}_{RL}}\right)^4 + \left(\frac{1}{\Lambda^{eq}_{RR}}\right)^4 =$$

Convert from LR terms To VA terms:

$$\left(\frac{1}{\Lambda^{eq}_{VV}}\right)^4 + \left(\frac{1}{\Lambda^{eq}_{VA}}\right)^4 + \left(\frac{1}{\Lambda^{eq}_{AV}}\right)^4 + \left(\frac{1}{\Lambda^{eq}_{AA}}\right)^4$$

Direct terms therefore set upper bounds in all of the C_1's and C_2's
(Interference terms are relatively insensitive to PV.)

$\Lambda_{ij} > 40\; TeV\; from\; LHC$: Direct terms set limits > 20 TeV
(LHC experiments fit only to a single Λ.)

Any Loopholes?

Are contact interactions appropriate for $Q^2 \sim \Lambda^2$?

Higher order term

$$\mathcal{L}_{eff} = \frac{g^2}{\Lambda^2} \sum_{i,j=L,R} \eta_{ij}^{eff} \bar{e}_i \gamma_\mu e_i \left(1 + \mathcal{O} \frac{4\pi\alpha s}{\Lambda^2} + \ldots \right).$$

$$\frac{d\sigma}{d\Omega} \sim \frac{\alpha^2 s}{4\alpha^2 \Lambda^4} (1 + \cos\theta)^2 \left[1 + \mathcal{O} 4\pi\alpha (Q_q + r L_q L_e) \right]$$

Higher order term interferes with electroweak amplitude

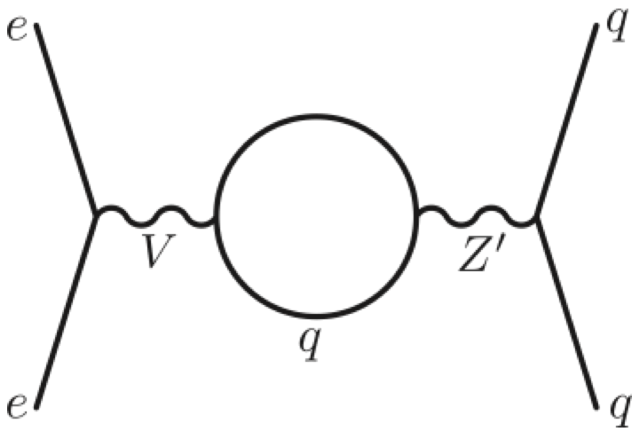
Another Loophole: Is there new physics below 2 TeV that LHC has failed to uncover??

- Leptophobic Z'?
- Z' with exotic decays that make it wide?
- Dark light

Note: $A_Z/A_\gamma \approx Q^2 \ for \ Q^2 \ll M_Z$;

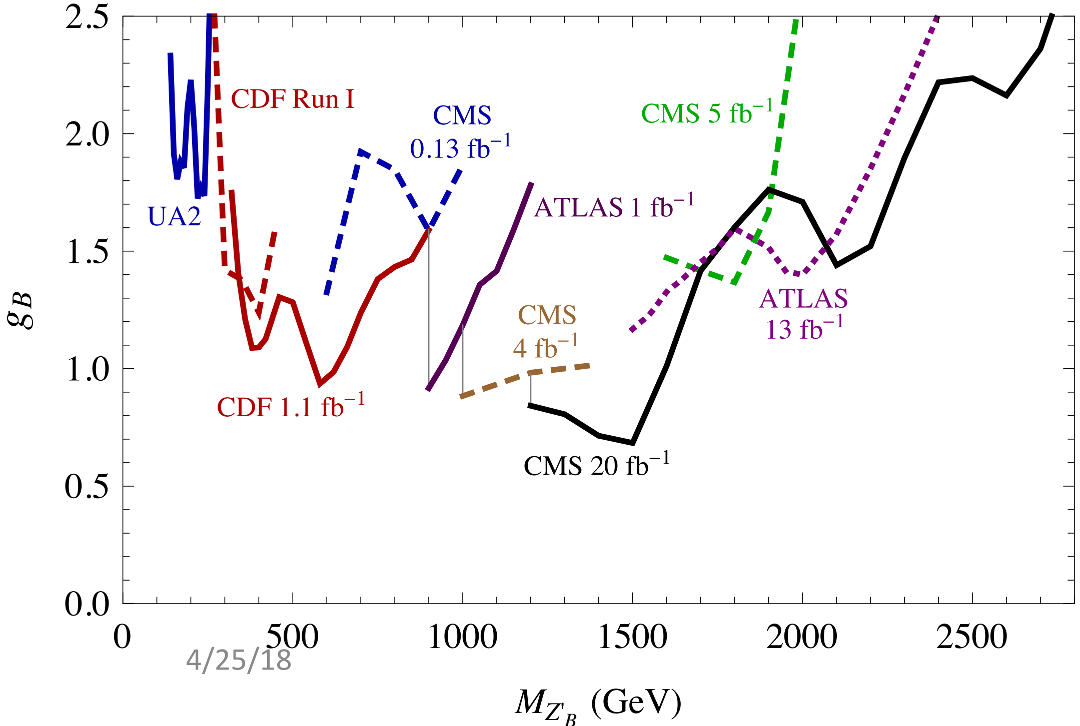
: $A_Z/A_\gamma \approx 1 \ for \ Q^2 \gg M_Z$

New Physics and c_2's



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 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

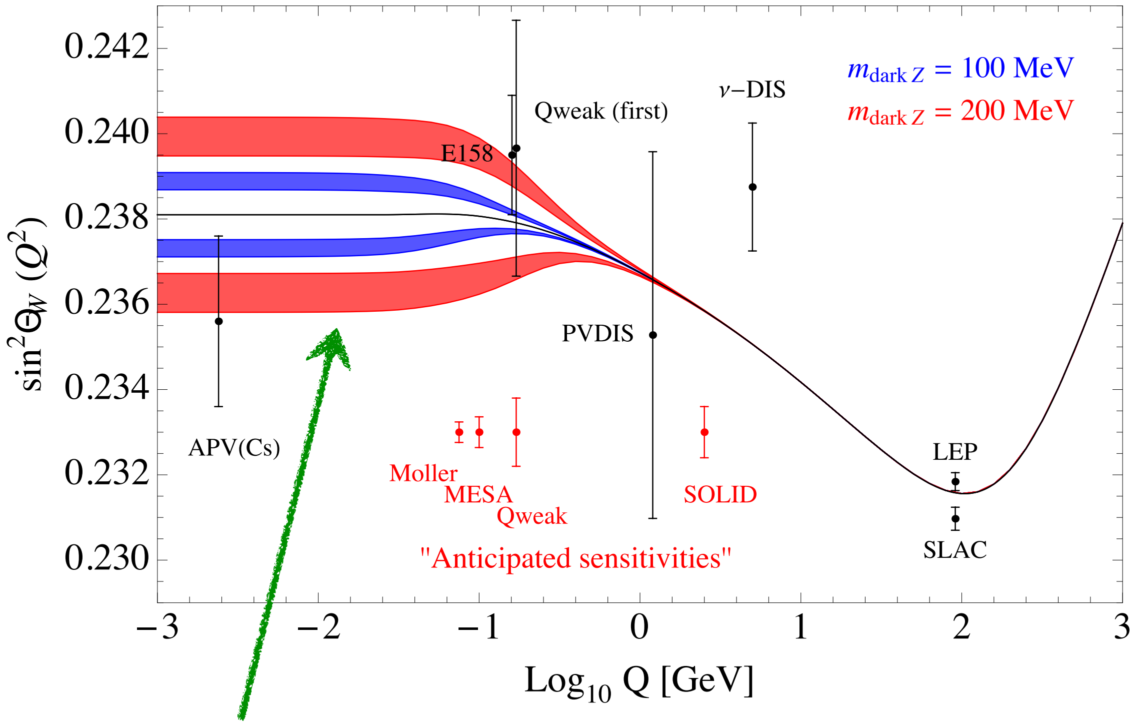
arXiv:1203.1102v1
Buckley and Ramsey-Musolf

Impact of Leptophobic Z' Bosons on PVDIS

- Justifies measuring C_2's
- Example of low energy physics that LHC cannot see
- Not a popular model

Weak angle shift for Low Q^2 due to Dark Z′

[Davoudiasl, Lee, Marciano (2014)]



Invisibly-decaying Dark Z.

Colored regions are predictions for the Weak angle due to the g-2 Δa_μ shift.

$$\Delta \sin^2\theta_W(Q^2) \simeq -0.42\,\varepsilon\delta \frac{m_Z}{m_{Z'}} \frac{1}{1+Q^2/m_{Z'}^2}$$

Slide adapted from Lee, PAVI-14

Deviations from the SM prediction (due to Dark Z) can appear **"only" in the Low-E experiments.**

For the Low-Q^2 Parity Test (measuring Weak angle), we can use

(i) Atomic Parity Violation (Cs, …)

(ii) Low-Q^2 PVES (E158, Qweak, MESA P2, Moller, SoLID…)

independent of Z' decay BR (good for both visibly/invisibly decaying Z').

New Models Extend Q^2 Range

Qweak data provides
Important limit.

Low Q^2 Weak Mixing Angle Measurements and Rare Higgs Decays

Hooman Davoudiasl,[1] Hye-Sung Lee,[2] and William J. Marciano[1]
[1] *Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2] *CERN, Theory Division, CH-1211 Geneva 23, Switzerland*

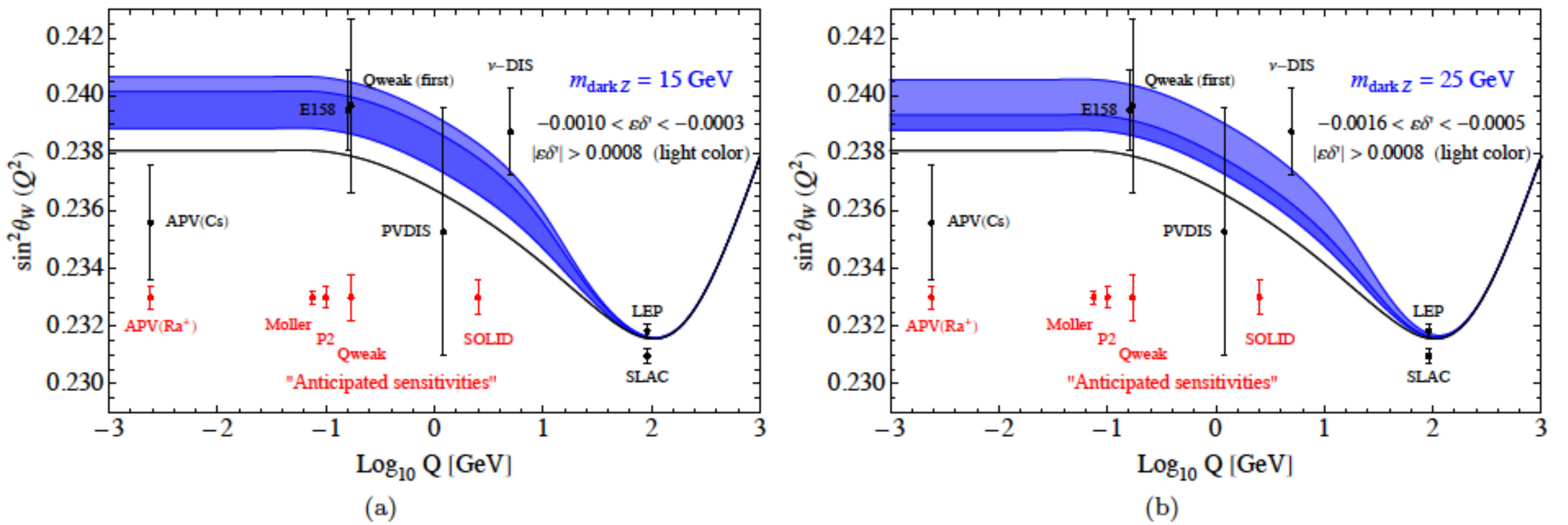


FIG. 3. Effective weak mixing angle running as a function of Q^2 shift (the blue band) due to an intermediate mass Z_d for (a) $m_{Z_d} = 15$ GeV and (b) $m_{Z_d} = 25$ GeV for 1 sigma fit to $\varepsilon\delta'$ in Eq. (12). The lightly shaded area in each band corresponds to choice of parameters that is in some tension with precision constraints (see text for more details).

Lorentz Invariance Violation

R. Lenhert: Effect in Moller scattering.
Similar effect should also be observable in PVDIS.
Theory features many new parameters.
LHC data is irrelevant.

$$\delta A(t) = \frac{G_F}{\sqrt{2}\pi\alpha} \frac{E_k\, y\,(1-y)\sin^2\theta_W}{(y^2-y+1)^2}\, \vec{k}(t)\cdot\vec{\xi}$$
$$= \frac{G_F}{\sqrt{2}\pi\alpha} \frac{E_k^2\, y\,(1-y)\sin^2\theta_W}{(y^2-y+1)^2} \times$$
$$\left[\sqrt{\xi_X^2+\xi_Y^2}\sqrt{1-\cos^2\alpha\sin^2\chi}\,\cos\Omega_\oplus t + c_0\right]$$

SMEFT (wEFT) Analysis

- Recent publications on the subject.
- Discuss low Q^2 vs high Q^2 in ways I do not understand.
- Use spinors instead of Dirac wavefunctions.
- Use different variables: hard to connect to experiments; papers discuss C_1's but not C_2's. (One problem is correlations)

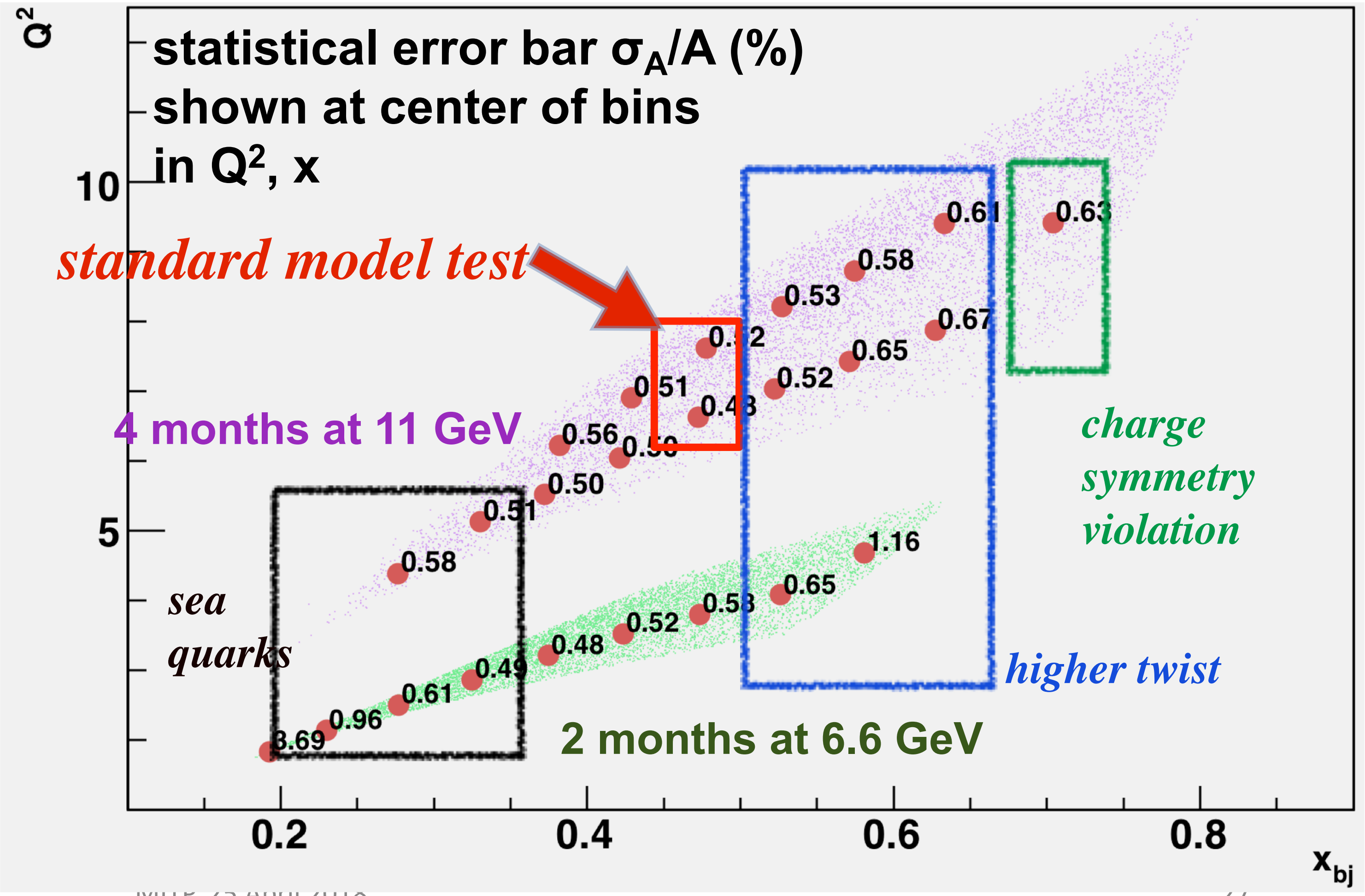
Review of Questions for PVDIS Physics Case

- What are the limits on the C_2's from LHC Drell-Yan data?
- Are these limits model dependent?
- Is there sub 2 TeV physics missed by the LHC?
- Are leptophobic Z' bosons useful motivation?
    - Example of sub 2 TeV physics
    - Sensitive to C_2's, not C_1's
    - Leptophobic Z' models were not motivated by SoLID
    - Models are not very popular

Criteria for Evaluating PVES Experiments

- Improvement over previous experiment
- $\Delta C/C$
- ΔC
- $\Delta \sin^2\theta_W$
- Models

Kinematic Acceptance



Untangling the Physics

Kinematic dependence of physics topics

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

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

Charge Symmetry Violation

We already know CSV exists:

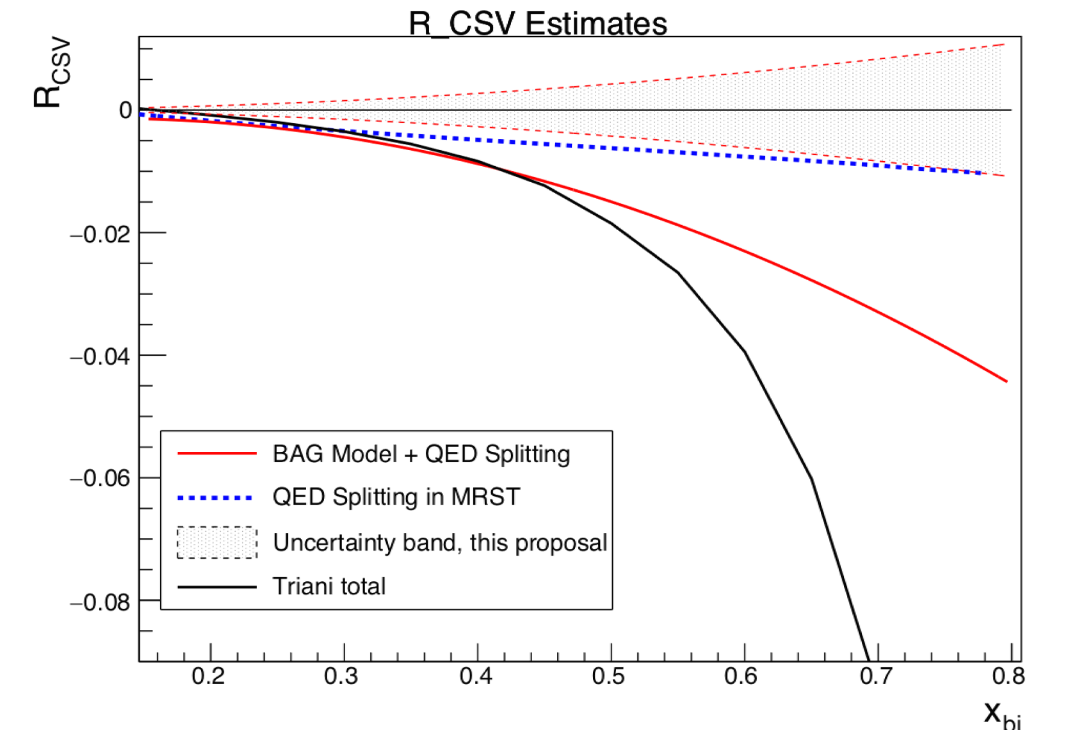
- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

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

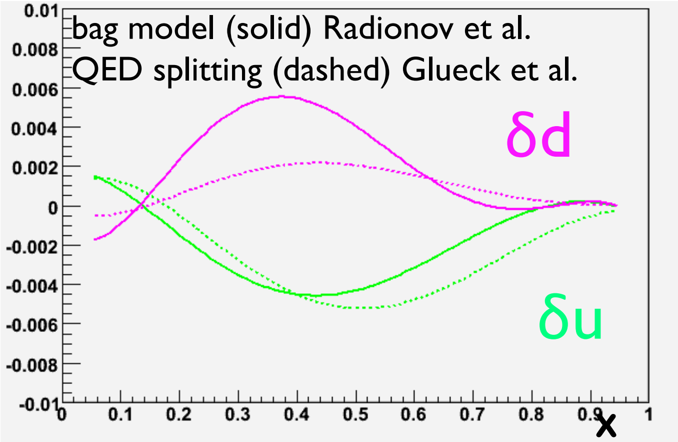
- Direct sensitivity to parton-level CSV
- Important implications for PDF's
- Could be partial explanation of the NuTeV anomaly

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

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



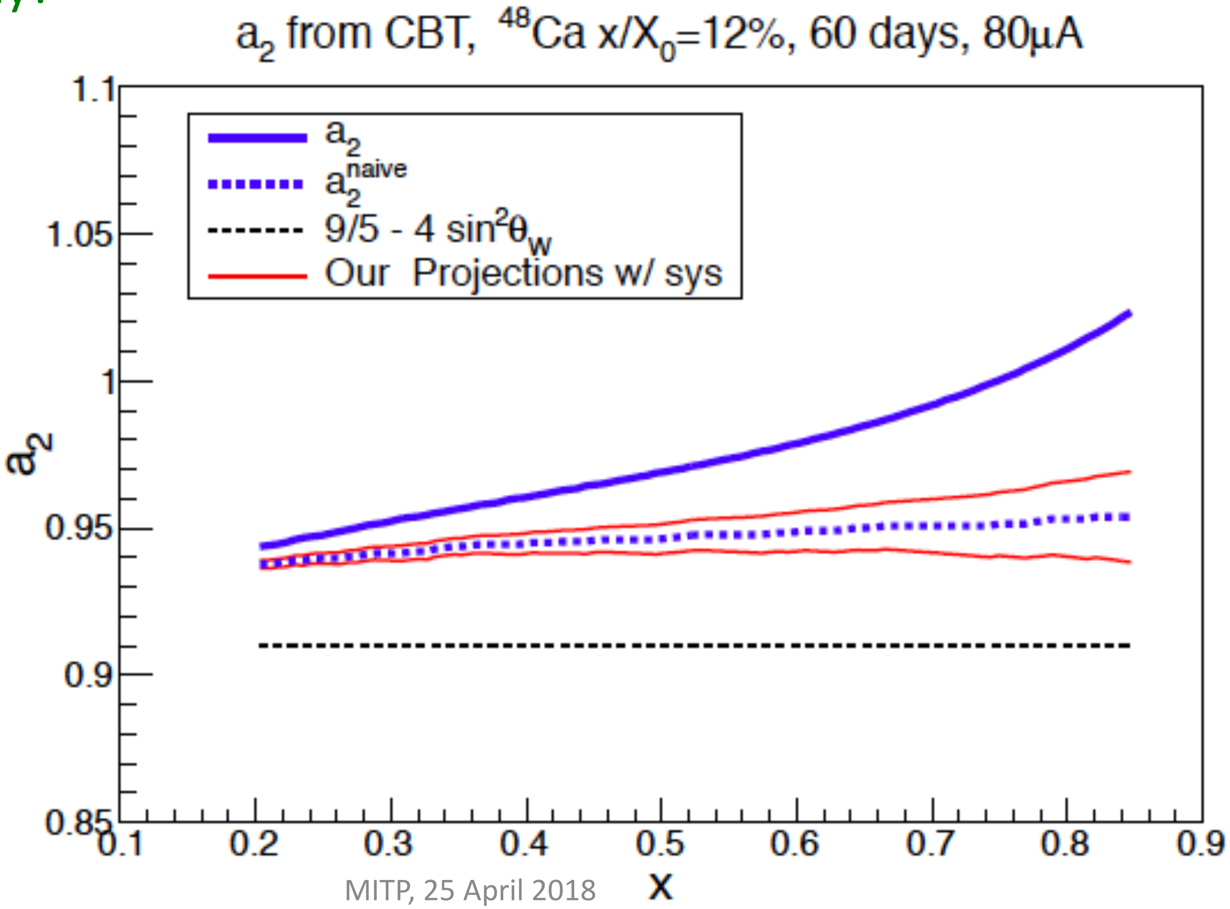
Sensitivity will be enhanced if u+d falls off more rapidly than δu-δd as x → 1



Significant effects are predicted at high x

Isovector EMC Effect (New Proposal)

Additional contribution to NuTeV anomaly?



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)

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

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

Isospin decomposition
before using PDF's

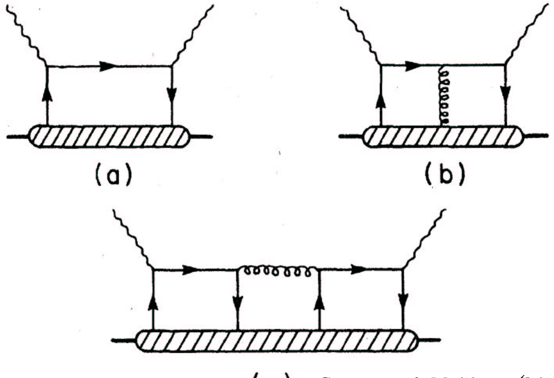
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

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

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

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



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

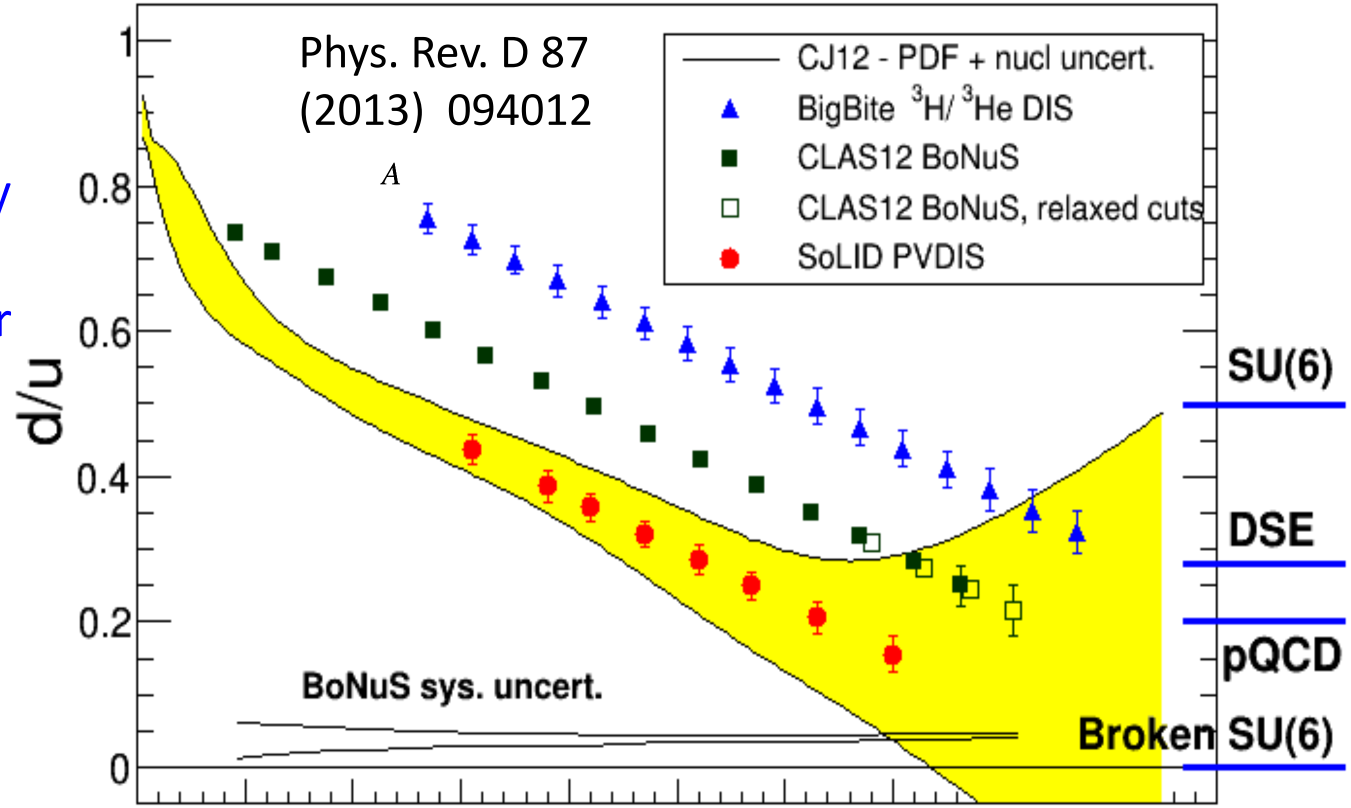
Use ν data for small b(x) term.

PVIDS with the Proton

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

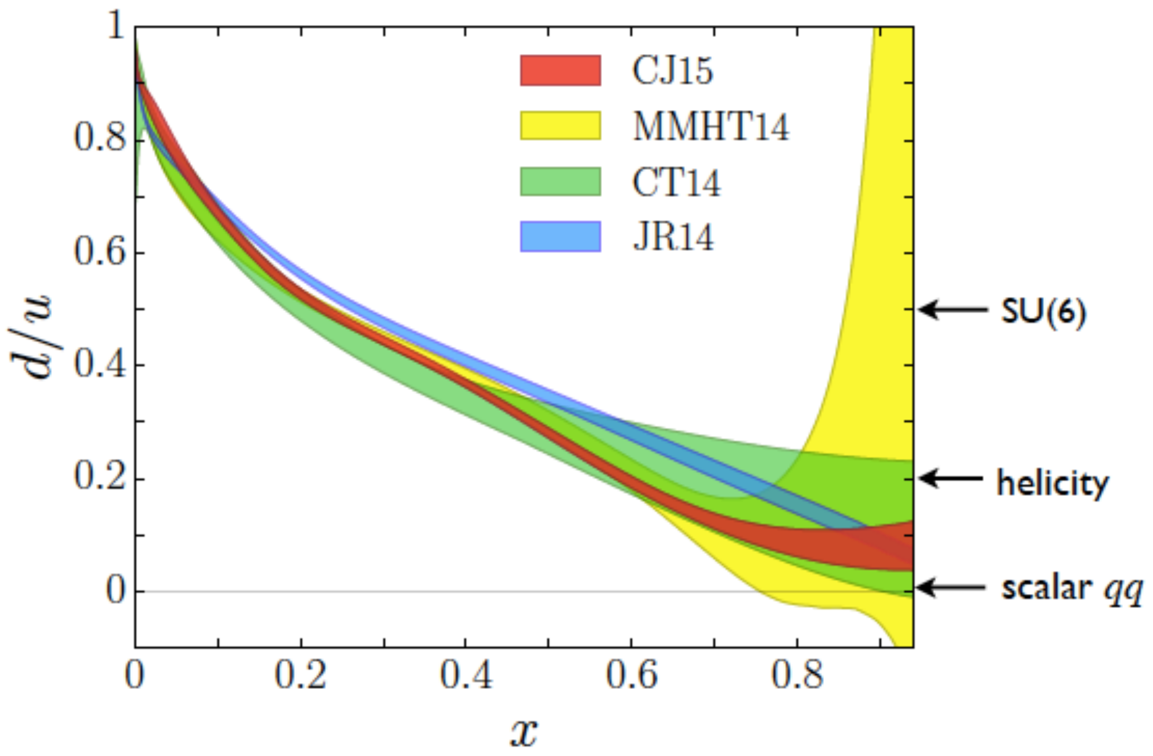
$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

PVDIS is complementary to the rest of the JLAb d/u program: no nuclear effects



Recent Analysis with Fermilab Data

Could improved d/u determination improve W mass measurement and hence $\sin^2\theta_W$?



Marathon 3He/3H data taken at Jlab; should be released soon. Will provide a real measure of possible impact

Summary of Motivation for PVDIS

- Limits on Λ. Favored by Jlab PAC, management.
- EMC effect on ^{48}Ca. My favorite, but not approved by Jlab PAC.
- CSV. Rule out semi-reasonable range.
- HT. Connect to np→dγ? Limited literature, no models with big effects.
- d/u. Will Marathon data help motivate new data?

Signature of Neutral Weak Interaction in Electron Scattering - Parity Violation Asymmetry

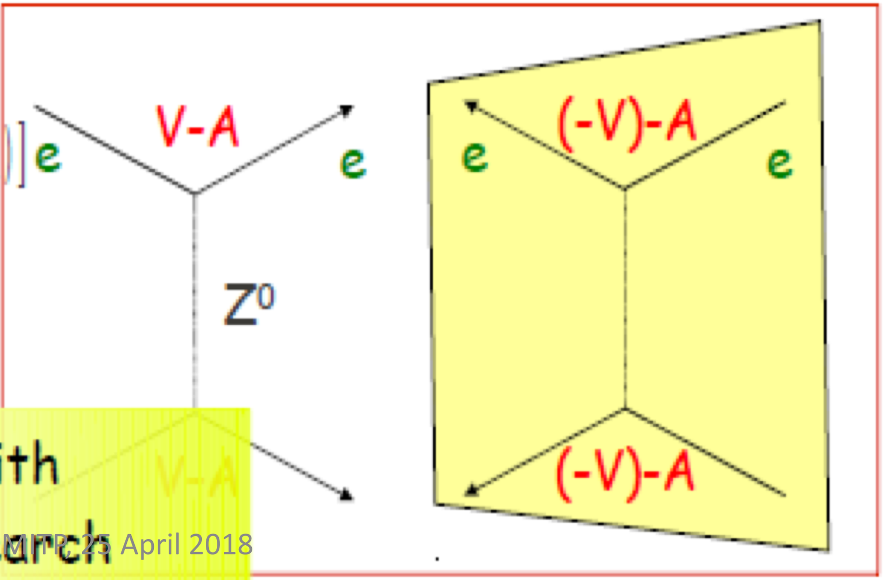
- In the Standard Model,
  - •weak interaction current = V(vector) minus A(axial-vector)
- PV comes from the product V×A
- In DIS: $A_{PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left[a_1 Y_1 + a_3 Y_3\right]$
- In the valence quark region:

$$a_1 = \frac{6}{5}\left[2C_{1u} - C_{1d}\right] \quad a_3 = \frac{6}{5}\left[\left(2C_{2u} - C_{2d}\right)\right]$$

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

e-q contact terms, both with potential in new physics search

fermions	$g_A^f = I_3$	$g_V^f = I_3 - 2Q\sin^2\theta_W$
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
$e-, \mu-$	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$



$$\frac{\eta_{ij}}{\Lambda^2} = \frac{1}{\Lambda_{ij}^2}$$

$$\frac{1}{\Lambda_{LR}^2} = \sum A^{LR}{}_{ij} C_{ij}$$

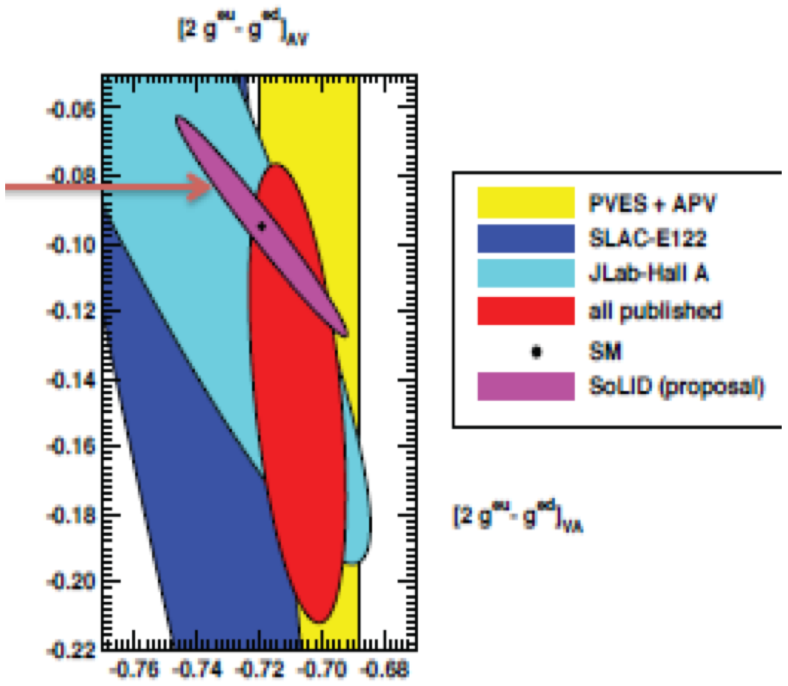
$$C_{VA}^{eq} \to \frac{1}{(\Lambda_{VA}^{eq})^2}$$

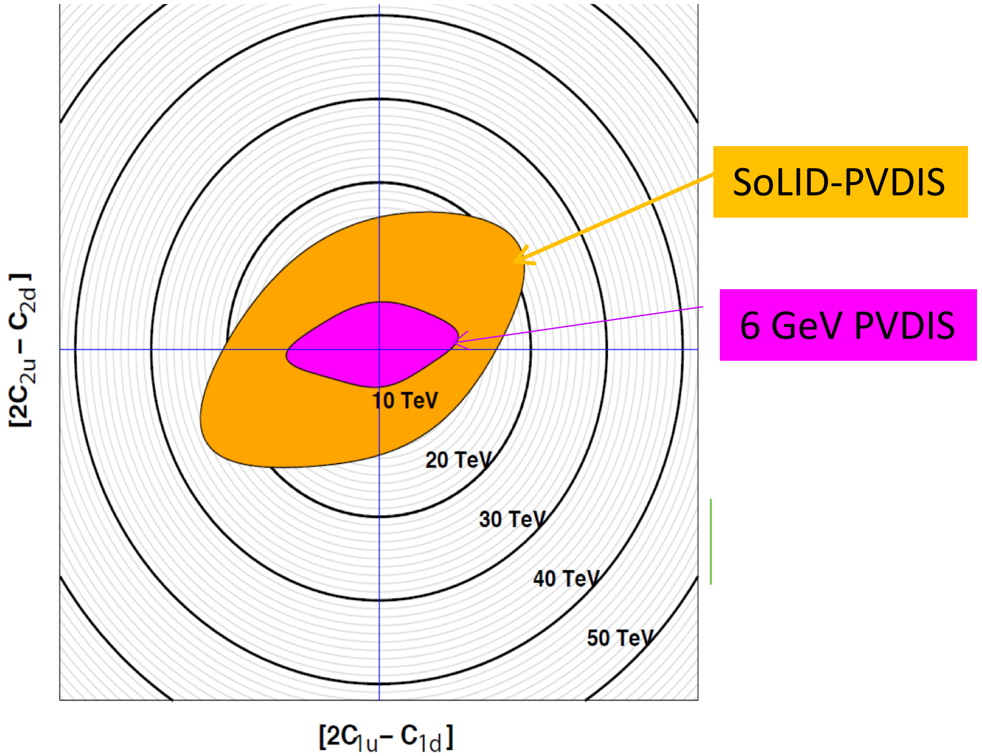
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ → ***PV elastic e-p scattering, Atomic parity violation***

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

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

Parity Violation with SoLID





PVDIS asymmetry has two terms:
1) C_{2q} weak couplings, test of Standard Model
2) Unique precision information on quark structure of nucleon

Mass reach in a composite model, SoLID-PVDIS ~ 20 TeV, sensitivity match LHC reach with complementary Chiral and flavor combinations

Is the lack of a compelling model a good reason to ignore measuring a fundamental coupling?