

The Physics Case for PVDIS with SoLID

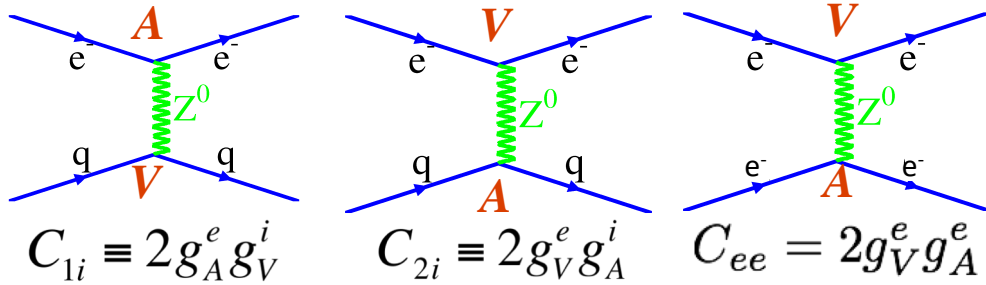
and lepton pair production at the LHC

P. A. Souder

Outline

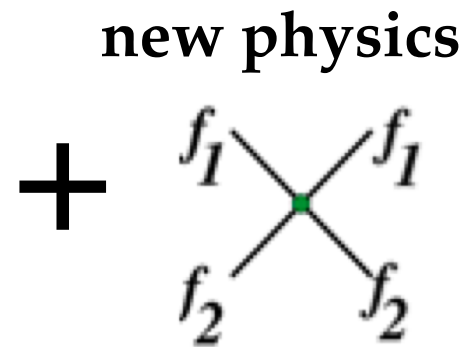
- The solid spectrometer and experimental program
- BSM Physics and PVDIS
- Implications of LHC Data
- PVES as a probe of hadronic structure (and BSM physics)

PVES and Contact Interactions



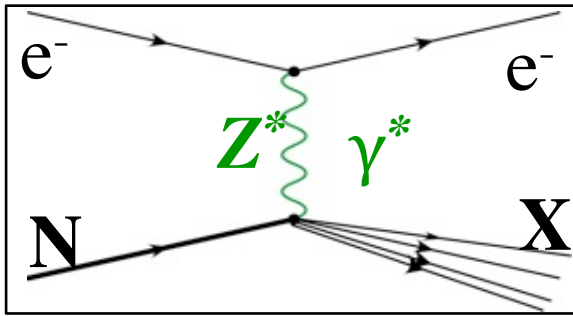
$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}} [\bar{e} \gamma^\mu \gamma_5 e (C_{1u} \bar{u} \gamma_\mu u + C_{1d} \bar{d} \gamma_\mu d) + \bar{e} \gamma^\mu e (C_{2u} \bar{u} \gamma_\mu \gamma_5 u + C_{2d} \bar{d} \gamma_\mu \gamma_5 d) + C_{ee} (e \gamma^\mu \gamma_5 e \bar{e} \gamma_\mu e)]$$

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



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

Theory of PVDIS



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

$$x \equiv x_{Bjorken}$$

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

$$Q^2 \gg 1 \text{ GeV}^2, W^2 \gg 4 \text{ GeV}^2 \quad A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} [a(x) + f(y)b(x)]$$

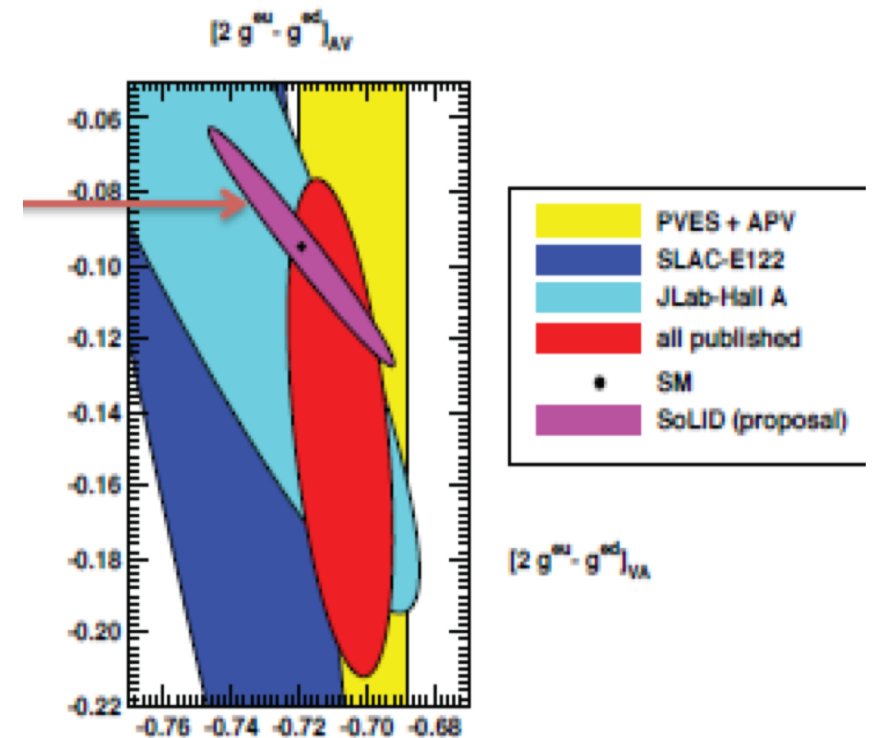
$$\begin{aligned} A_{iso} &= \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \\ &= - \left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}} \right) \frac{2C_{1u} - C_{1d}(1 + R_s) + Y(2C_{2u} - C_{2d})R_v}{5 + R_s} \end{aligned}$$

$$\begin{aligned} R_s(x) &= \frac{2S(x)}{U(x) + D(x)} \xrightarrow{\text{Large } x} 0 \\ R_v(x) &= \frac{u_v(x) + d_v(x)}{U(x) + D(x)} \xrightarrow{\text{Large } x} 1 \end{aligned}$$

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

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?

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

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

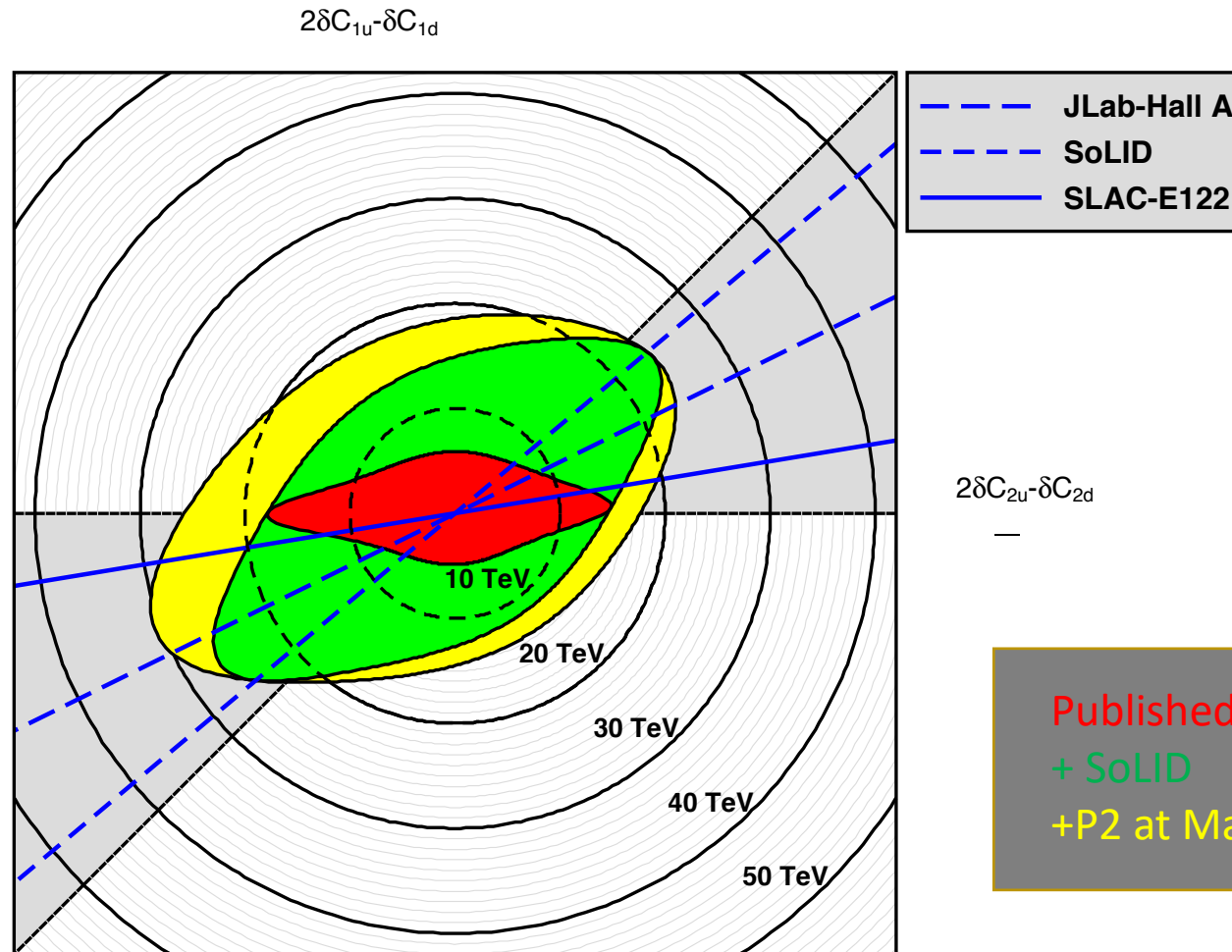
$$\eta_{ij}/\Lambda \rightarrow 1/\Lambda_{LR} \rightarrow 1/\Lambda_{VA} \rightarrow \Delta C$$

Constants related by 4X4 matrices

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

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

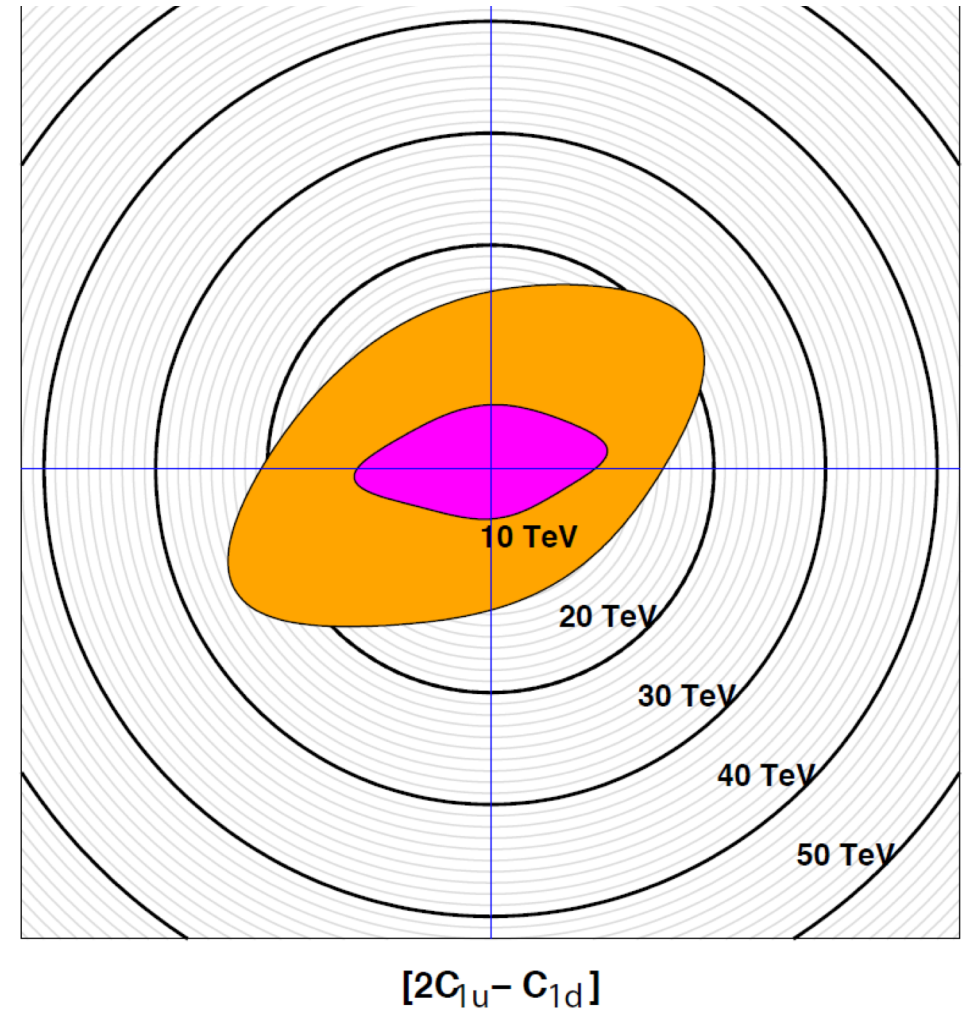
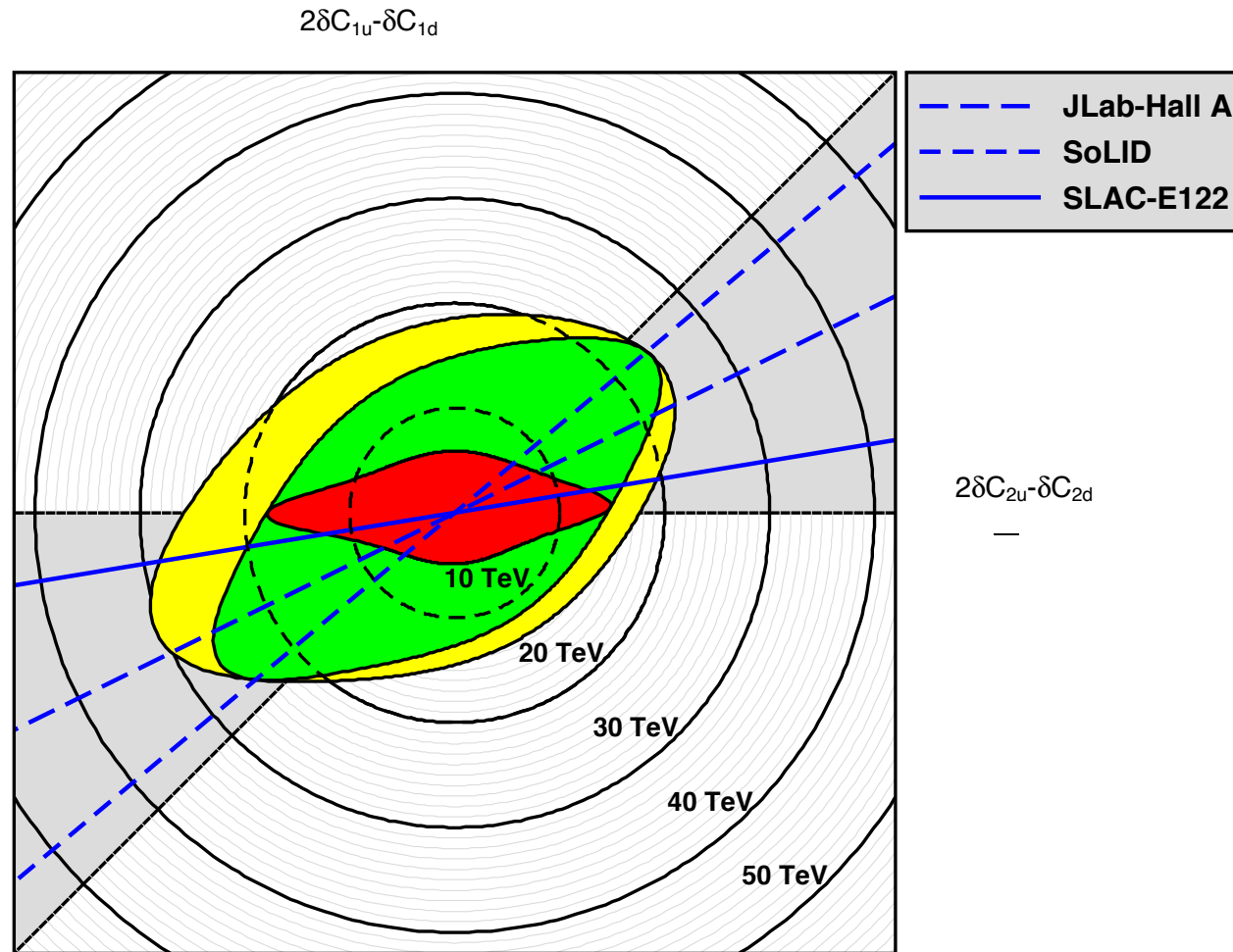
Sensitivity to Λ in Composite Models (LHC)



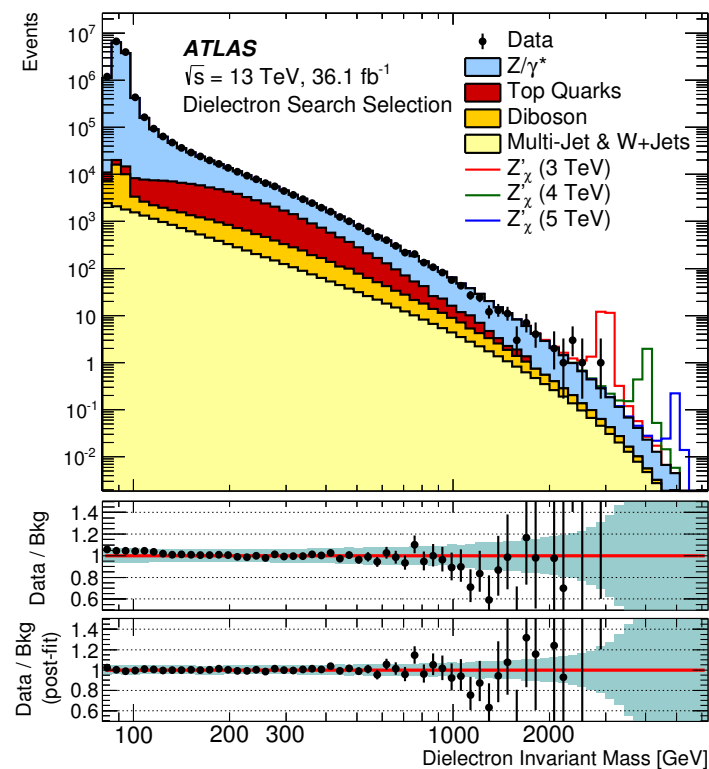
Sensitive to very large values of Λ , comparable to LHC data.

LHC $pp \rightarrow e^+e^-$ data includes dimension 8 operators; SoLID is limited to dimension 6.

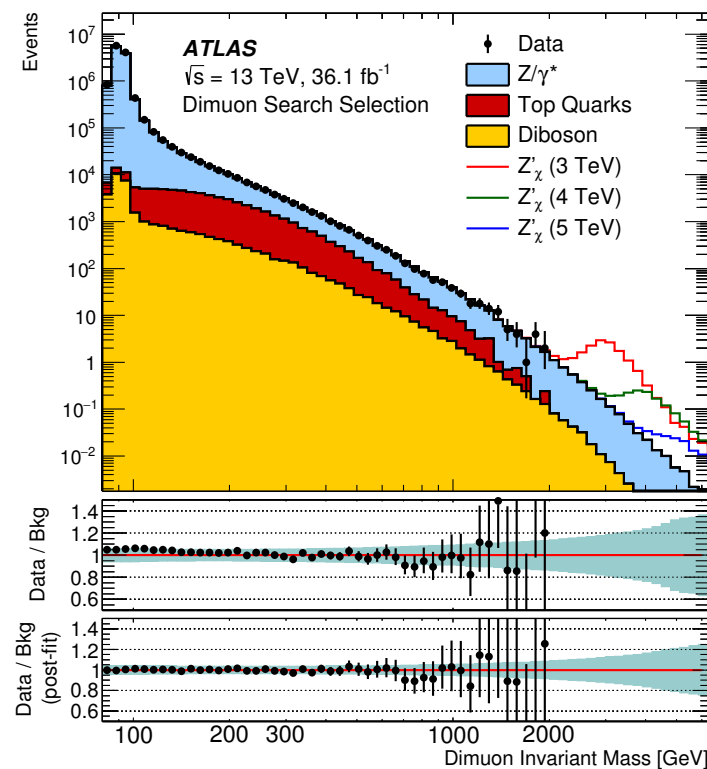
Compare Plots



Lepton Pair Production from ATLAS



(a)



(b)

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 $\Lambda \gg 2 \text{ TeV}$.
- Conclusion II: Need $g^2=4\pi$

Lepton Pair Production Cross Sections

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

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

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

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

Two Types of Terms

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

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:

Convert from LR terms
To VA terms:

$$\left(\frac{1}{\Lambda_{LL}^{eq}}\right)^4 + \left(\frac{1}{\Lambda_{LR}^{eq}}\right)^4 + \left(\frac{1}{\Lambda_{RL}^{eq}}\right)^4 + \left(\frac{1}{\Lambda_{RR}^{eq}}\right)^4 =$$
$$\left(\frac{1}{\Lambda_{VV}^{eq}}\right)^4 + \left(\frac{1}{\Lambda_{VA}^{eq}}\right)^4 + \left(\frac{1}{\Lambda_{AV}^{eq}}\right)^4 + \left(\frac{1}{\Lambda_{AA}^{eq}}\right)^4$$

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

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

Any Loopholes?

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

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

Higher order term

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

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

Conference Talks:

LHC: no new physics below 2 TeV

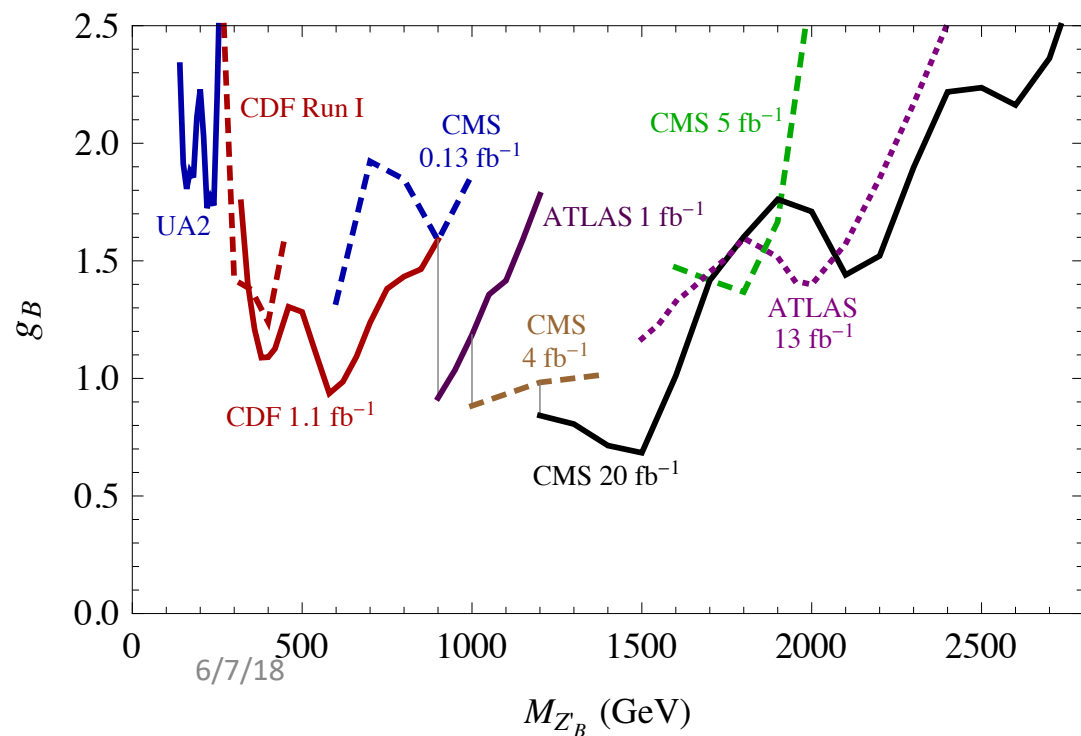
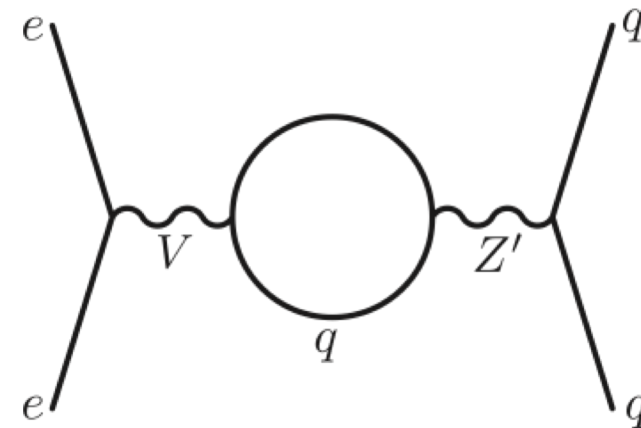
Dark Matter: all physics below 2 TeV

Note: $A_Z/A_\gamma \approx Q^2$ for $Q^2 \ll MZ$;
: $A_Z/A_\gamma \approx 1$ for $Q^2 \gg MZ$

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' doesn't 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](https://arxiv.org/abs/1203.1102v1)

Buckley and Ramsey-Musolf

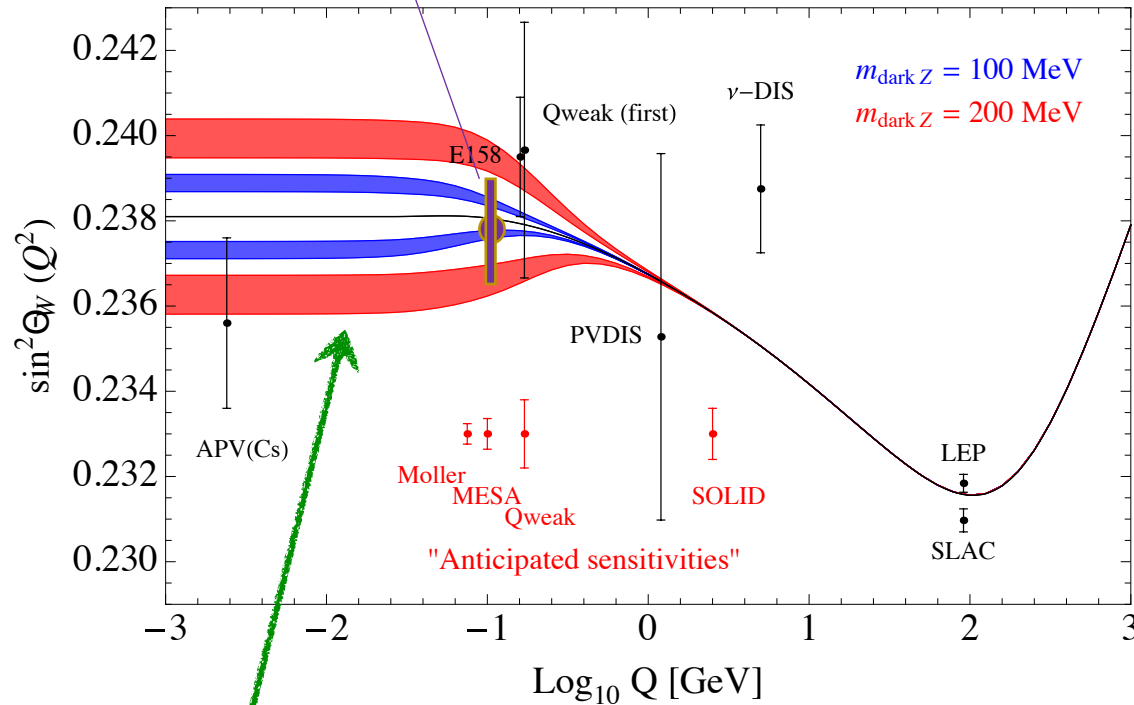
Impact of Leptophobic Z' Bosons on PVDIS

- 😊 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'

Qweak, 2018

[Davoudiasl, Lee, Marciano (2014)]



Invisibly-decaying Dark Z .

Colored regions are predictions for the Weak angle due to the $g-2 \Delta a_\mu$ 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. Marciano¹

¹Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA

²CERN, Theory Division, CH-1211 Geneva 23, Switzerland

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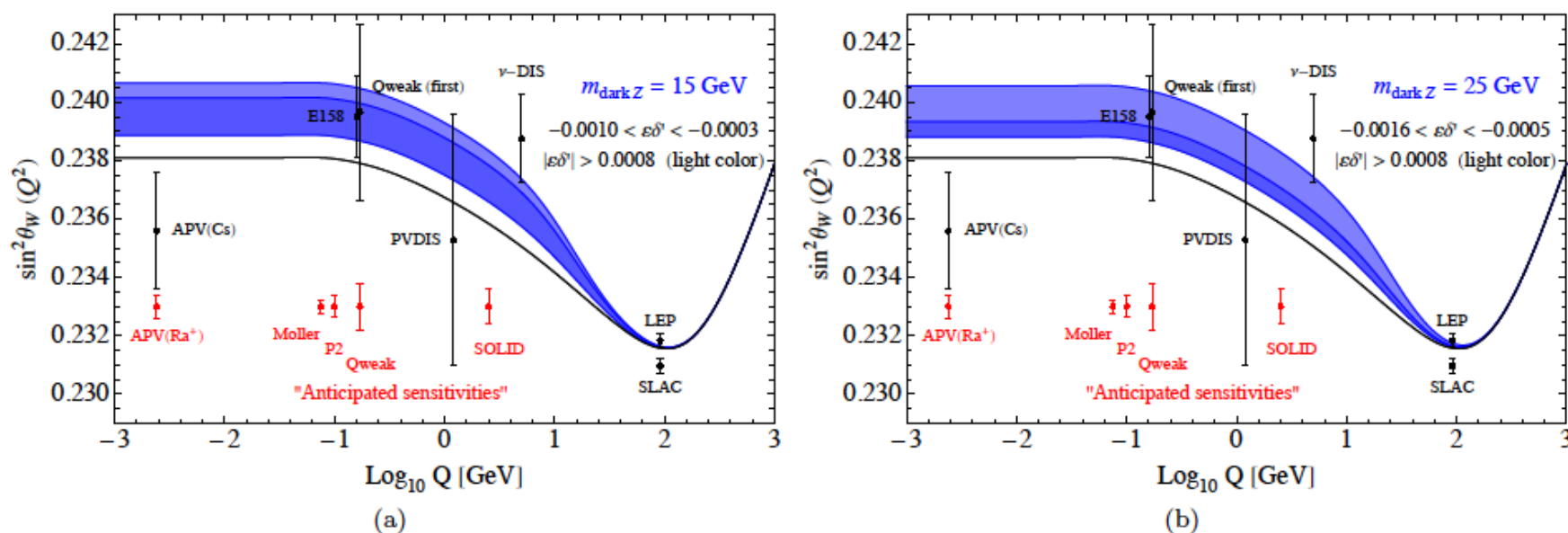


FIG. 3. Effective weak mixing angle running as a function of Q^2 shift (the blue band) due to an intermediate mass Z_d for (a) $m_{Z_d} = 15 \text{ GeV}$ and (b) $m_{Z_d} = 25 \text{ GeV}$ for 1 sigma fit to $\epsilon \delta'$ in Eq. (12). The lightly shaded area in each band corresponds to choice of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

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

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)

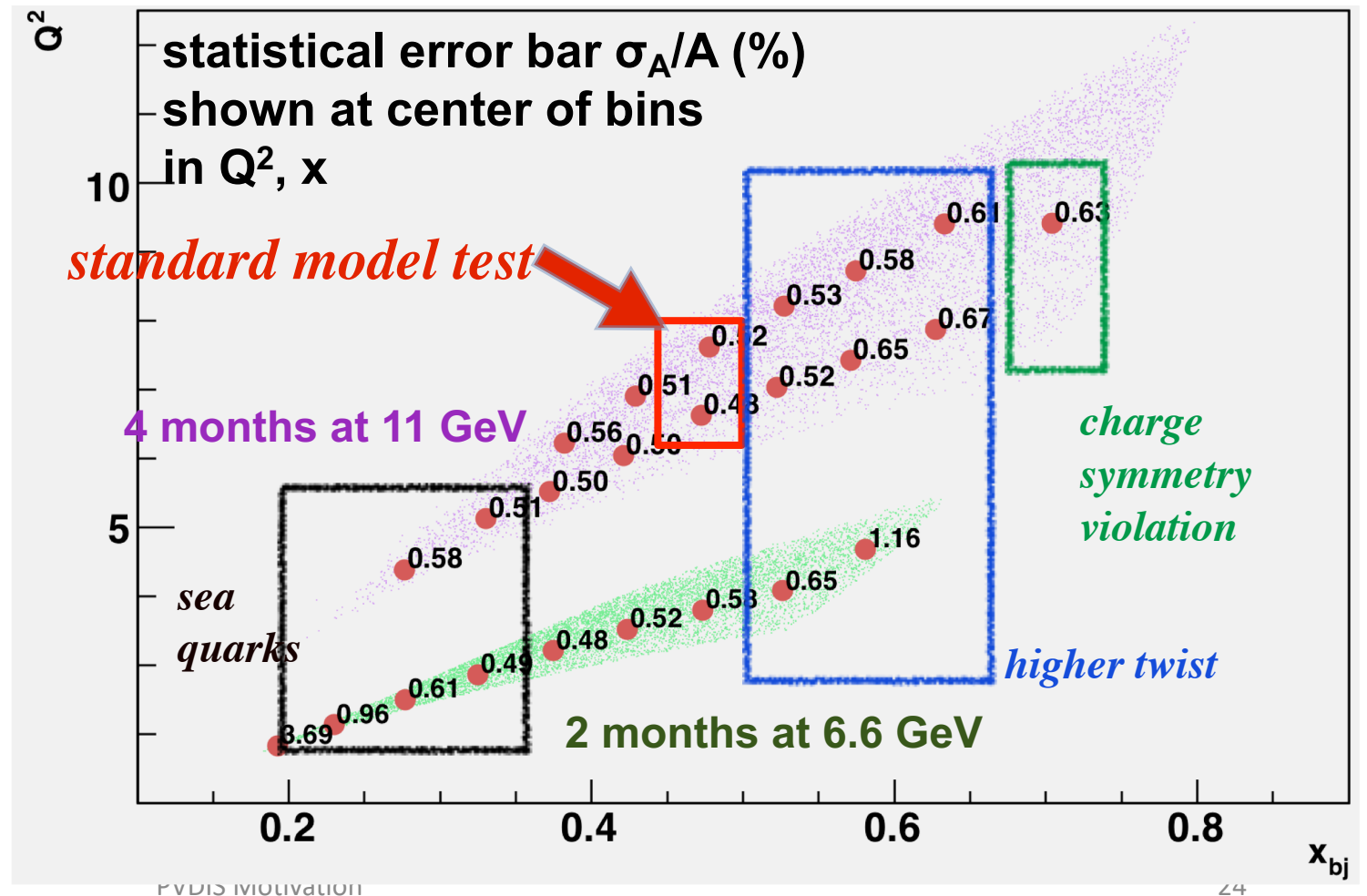
Review of Questions for PVDIS Physics Case

- 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 $\delta m = m_d - m_u \approx 4 \text{ MeV}$
 $\delta M = M_n - M_p \approx 1.3 \text{ MeV}$
- electromagnetic effects

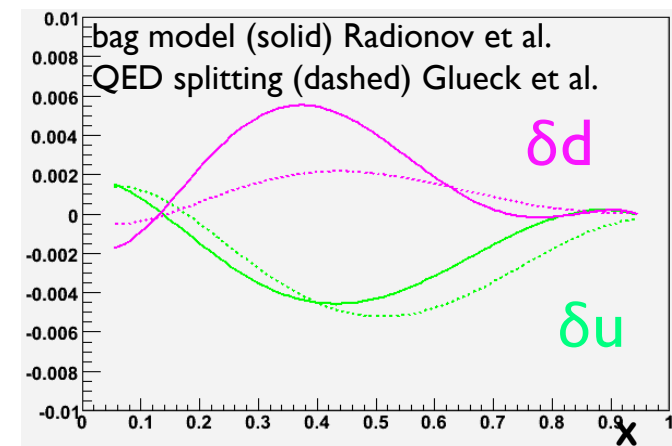
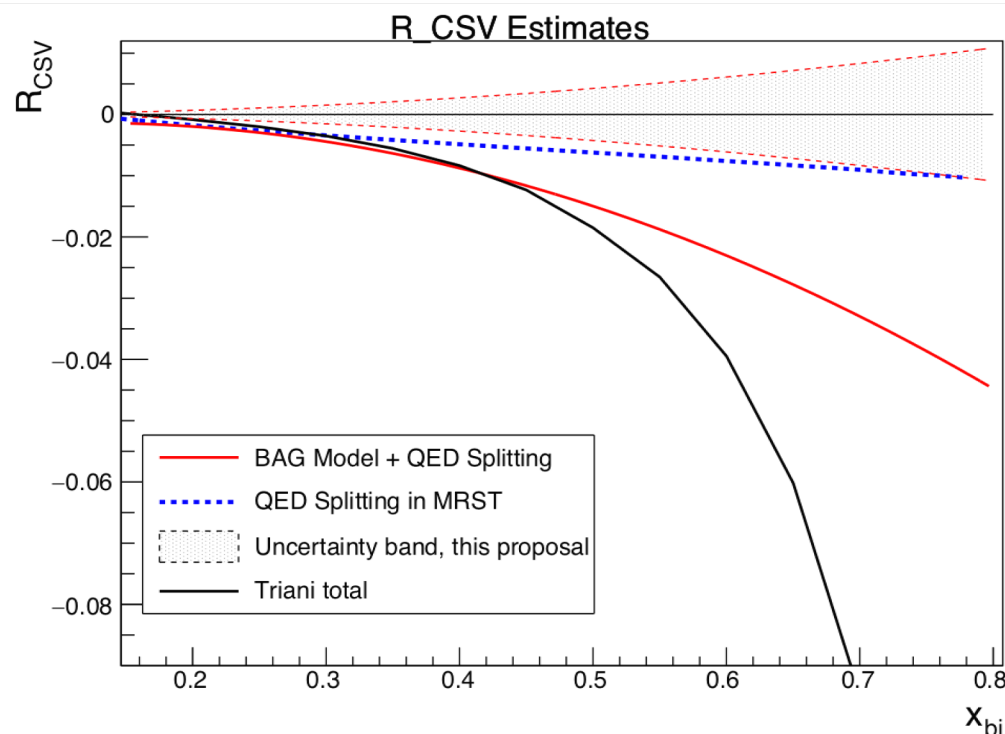
- Direct sensitivity to parton-level CSV
- Important implications for PDF's
- Could be partial explanation of the NuTeV anomaly

$$\begin{aligned} u^p(x) &\stackrel{?}{=} d^n(x) \Rightarrow \delta u(x) \equiv u^p(x) - d^n(x) \\ d^p(x) &\stackrel{?}{=} u^n(x) \Rightarrow \delta d(x) \equiv d^p(x) - u^n(x) \end{aligned}$$

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

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

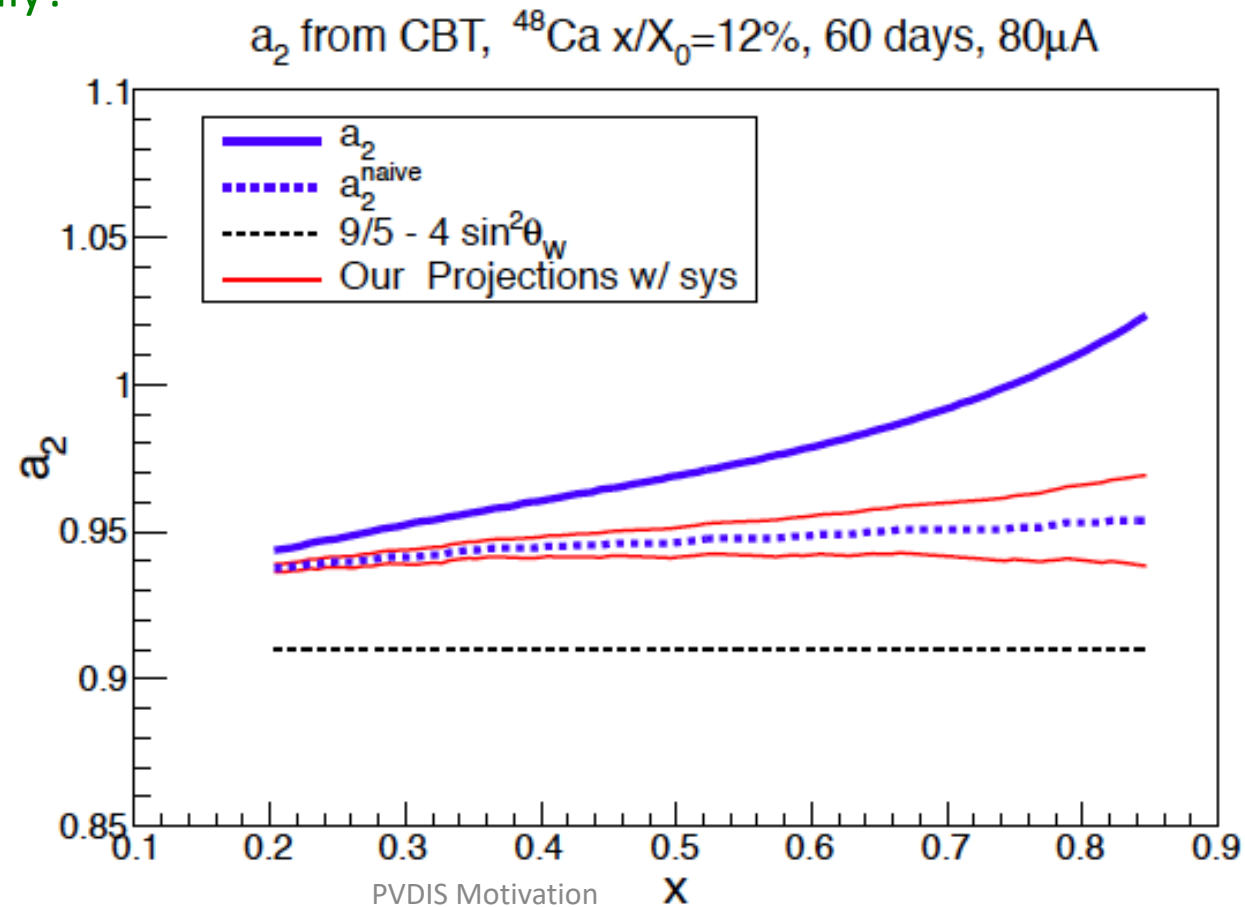
Sensitivity will be enhanced if $u+d$ falls off more rapidly than $\delta u - \delta d$ as $x \rightarrow 1$



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)

Isospin decomposition
before using PDF's

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

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

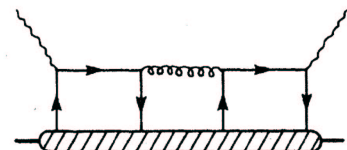
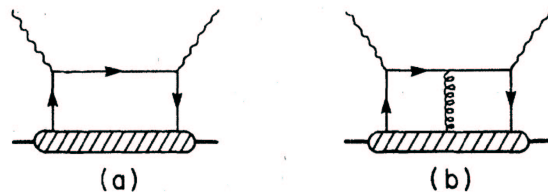
$$\langle VV \rangle = l_{\mu\nu} \int \langle D | V^\mu(x) V^\nu(0) | D \rangle e^{iq \cdot x} d^4x$$

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

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) 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

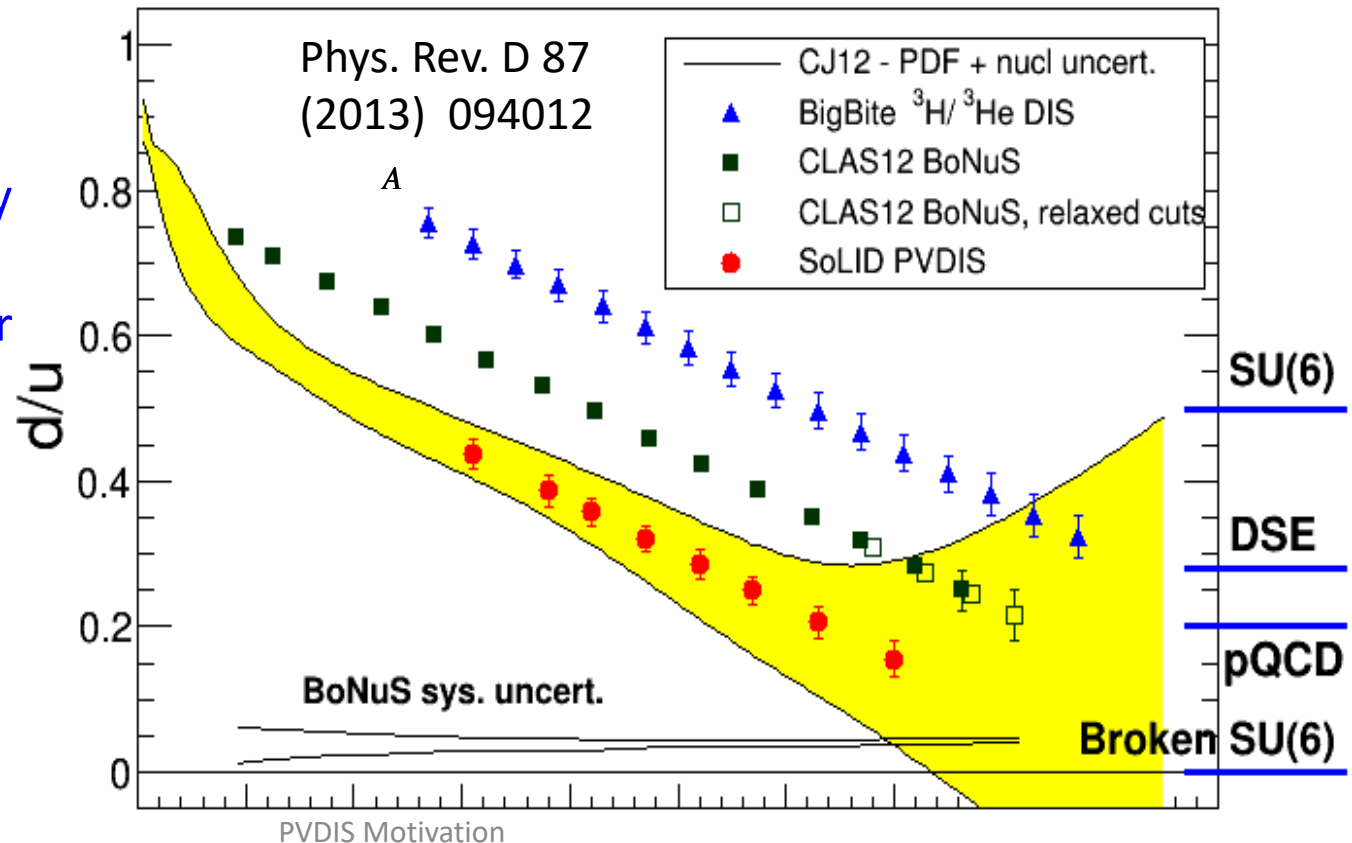
Use v data for small $b(x)$ term.

PVIDS with the Proton

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

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

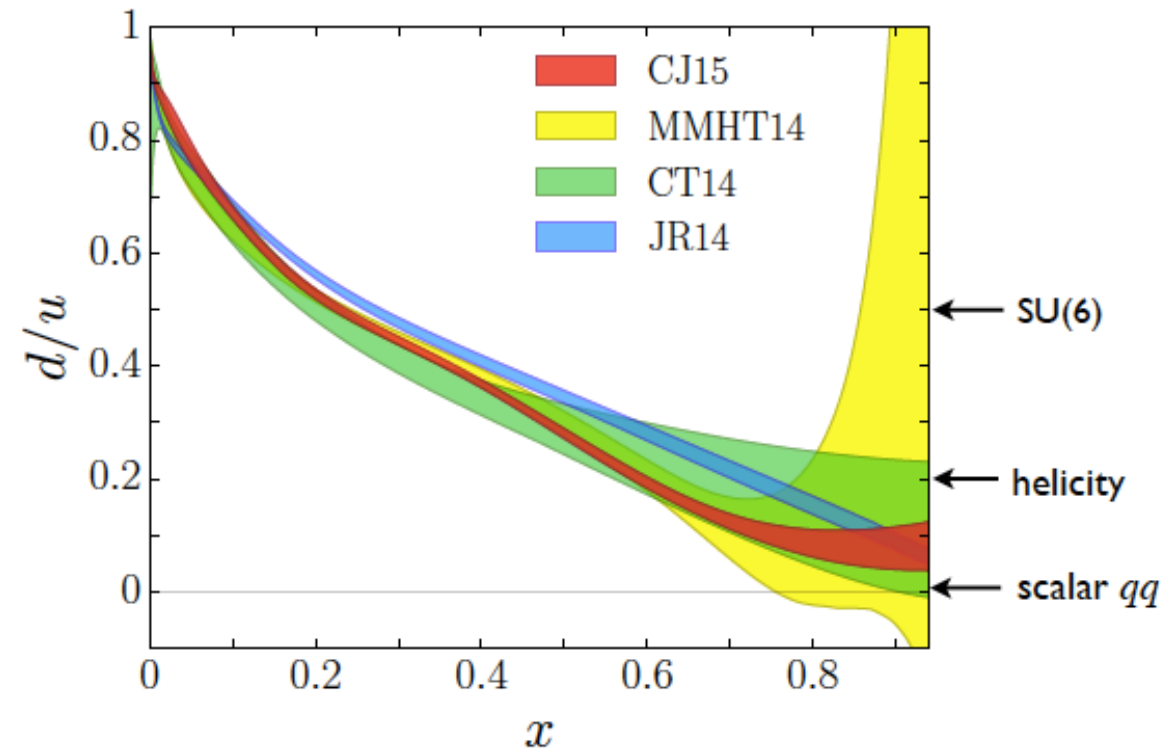
PVDIS is complementary
to the rest of the JLab
d/u program: no nuclear
effects



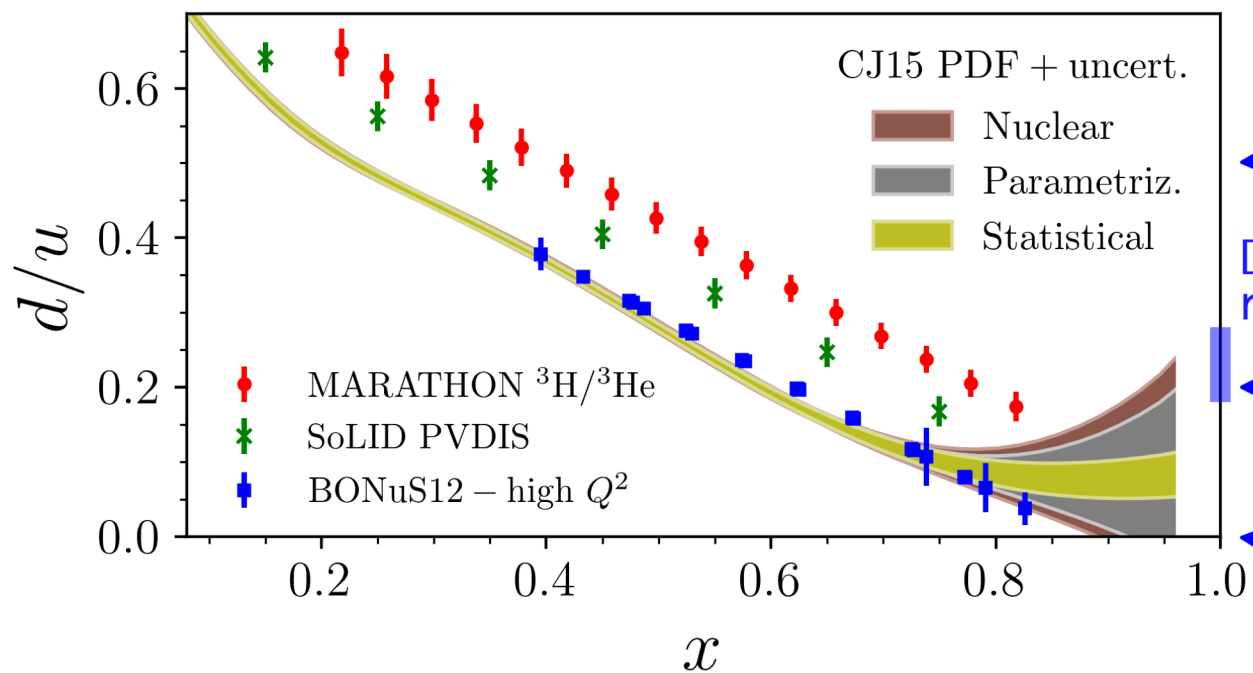
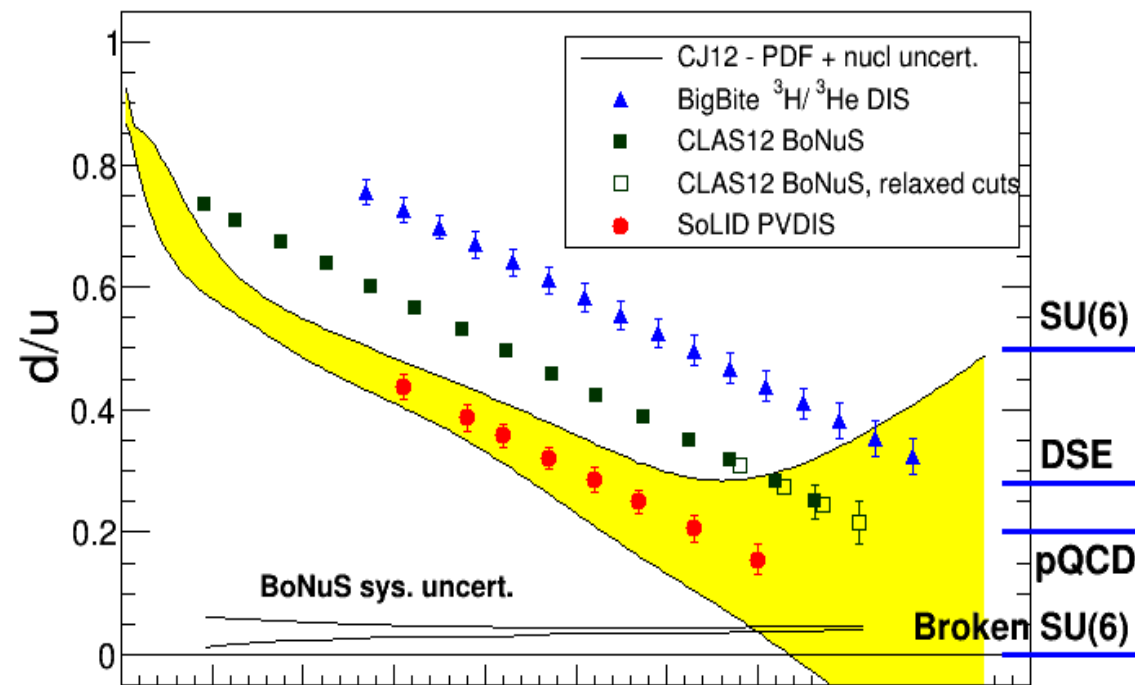
Recent Analysis with Fermilab Data

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



New CJ15 Plot



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 $n p \rightarrow d \gamma$? Limited literature, no models with big effects.
- d/u. Will Marathon data help motivate new data?

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

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

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

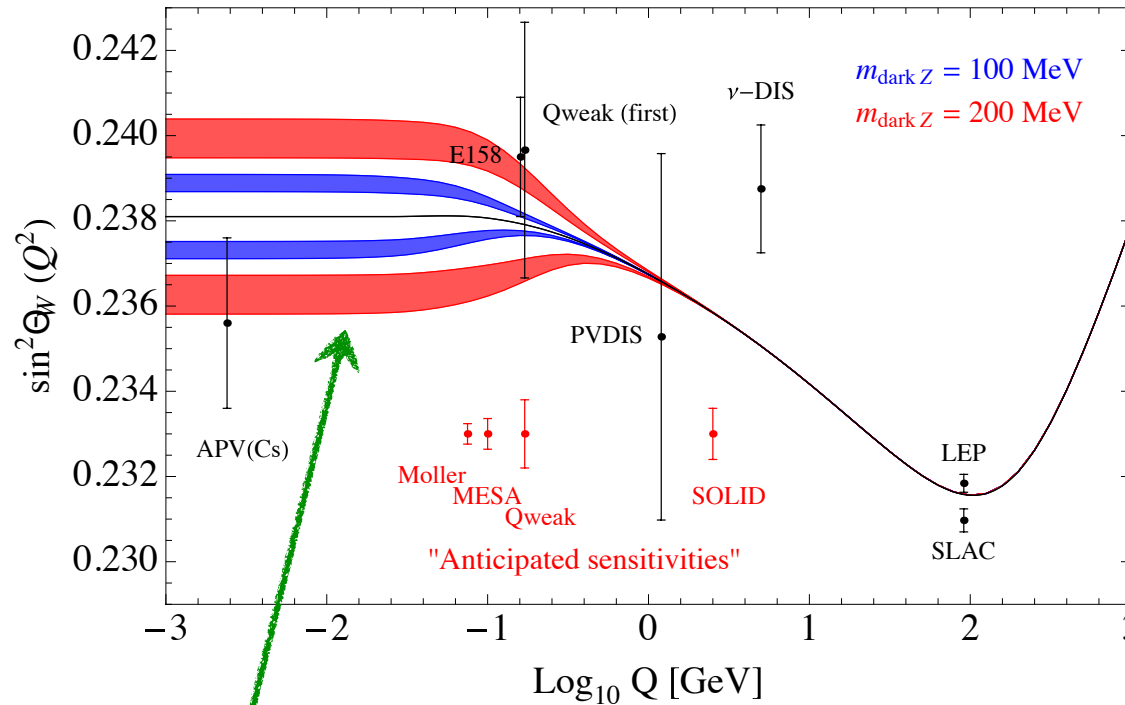
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow \text{PV elastic e-p scattering, Atomic parity violation}$$

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

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

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 $g-2 \Delta a_\mu$ shift.

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

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').

Published 6 GeV PVDIS data from JLab

6 GeV run results

$Q^2 \sim 1.1 \text{ GeV}^2$

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

$Q^2 \sim 1.9 \text{ GeV}^2$

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

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](#)

Sensitivity in terms of Λ

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

Oval: SoLID + Qweak

