# Probing BSM and High-x Physics with SoLID at JLab

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# Outline

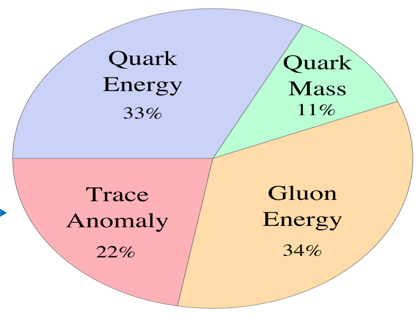
- The solid spectrometer and experimental program.
- BSM Physics and PVDIS.
- PVES as a probe of hadronic structure.

# Overview of SoLID in Hall A

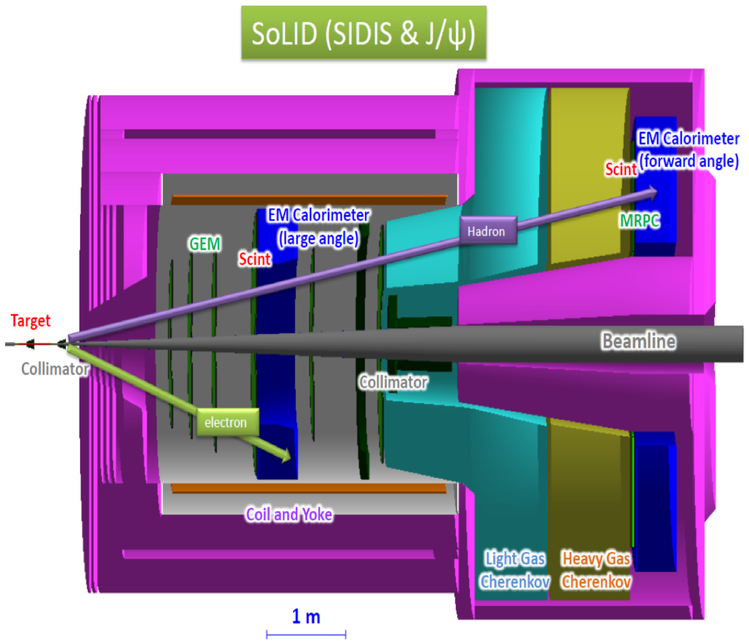
Solenoidal Large Intensity Device

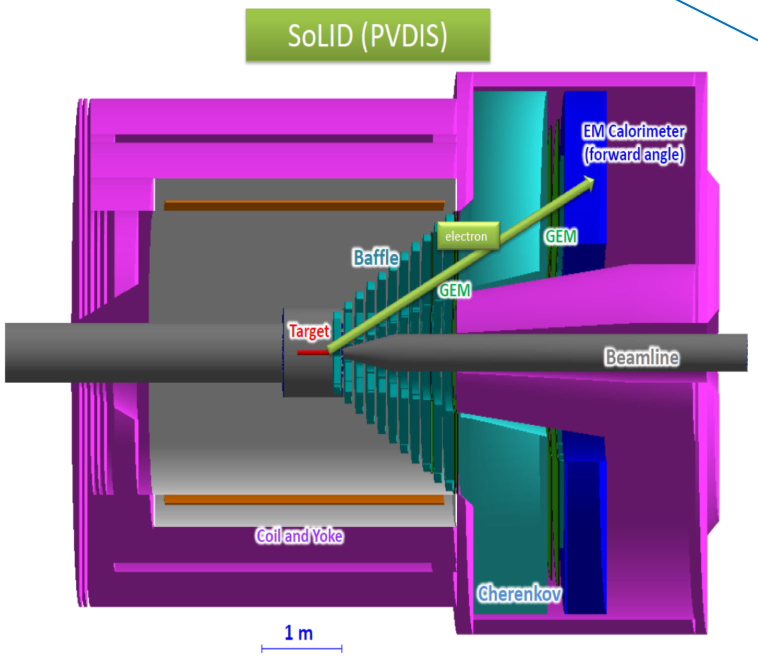
- Full exploitation of JLab 12 GeV Upgrade
  → A Large Acceptance Detector AND Can Handle High Luminosity ($10^{37}$-$10^{39}$)
  Take advantage of latest development in detectors , data acquisitions and simulations
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-x region and threshold J/ψ
- 5 highly rated experiments approved
  Three TMD experiments, one PVDIS, one J/ψ production
- Strong collaboration (250+ collaborators from 70+ institutes, 13 countries)
  Significant international contributions (Chinese collaboration)

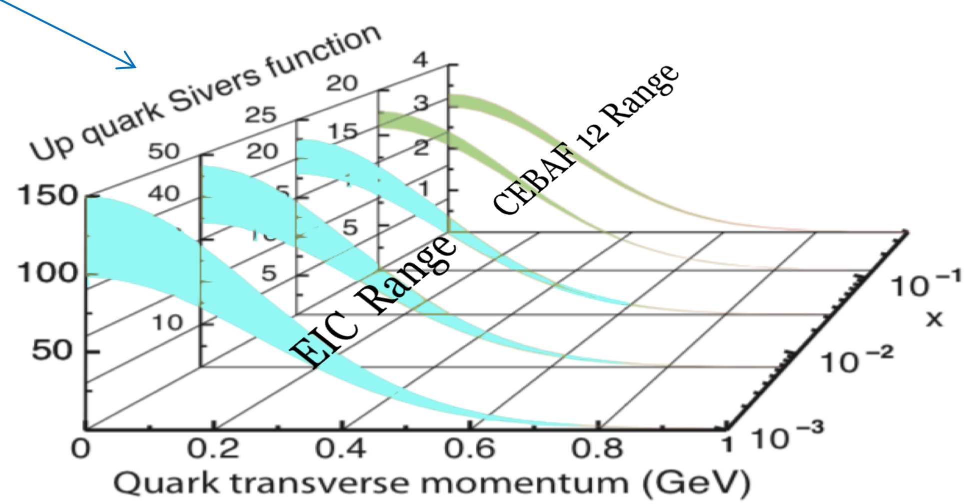
Contributions to proton mass




Compare to Υ at the EIC

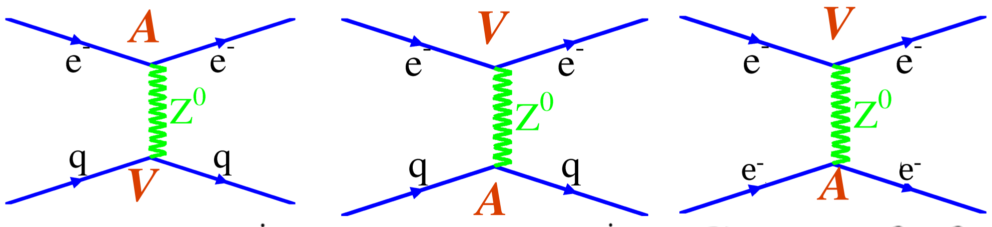



Complementary to the EIC

# PVES and Contact Interactions

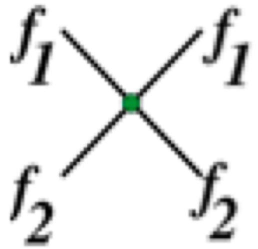



$C_{1i} \equiv 2 g_A^e g_V^i$ $C_{2i} \equiv 2 g_V^e g_A^i$ $C_{ee} = 2 g_V^e g_A^e$

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

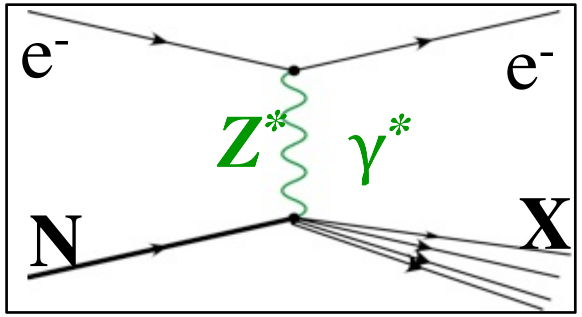
$$\begin{aligned} C_{1u} &= -\tfrac{1}{2} + \tfrac{4}{3} \sin^2\theta_W &\approx& -0.19 \\ C_{1d} &= \tfrac{1}{2} - \tfrac{2}{3} \sin^2\theta_W &\approx& 0.35 \\ C_{2u} &= -\tfrac{1}{2} + 2 \sin^2\theta_W &\approx& -0.04 \\ C_{2d} &= \tfrac{1}{2} - 2 \sin^2\theta_W &\approx& 0.04 \\ C_{ee} &= \frac{1}{2}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

**+ 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




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

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

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

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

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

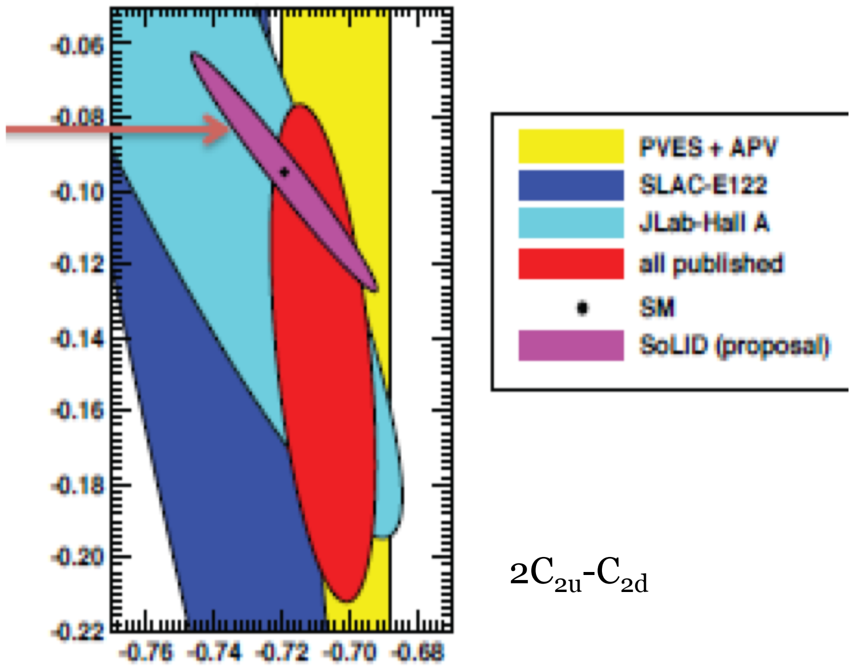
$$R_s(x) = \frac{2S(x)}{U(x) + D(x)} \xrightarrow{\text{Large } x} 0$$

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

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

# SoLID and the Low Energy PVES Program

- Measure each of the coupling constants as precisely as possible.
- The $C_2$'s ($g_{VA}$'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.

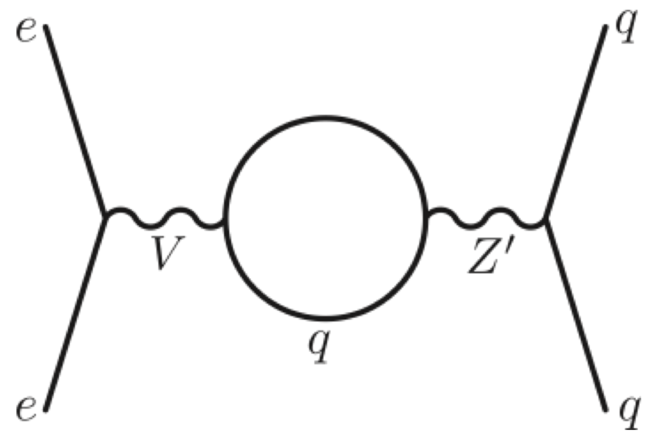



$2C_{2u}$-$C_{2d}$

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

# Is there new physics below 2 TeV that LHC has failed to uncover?

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



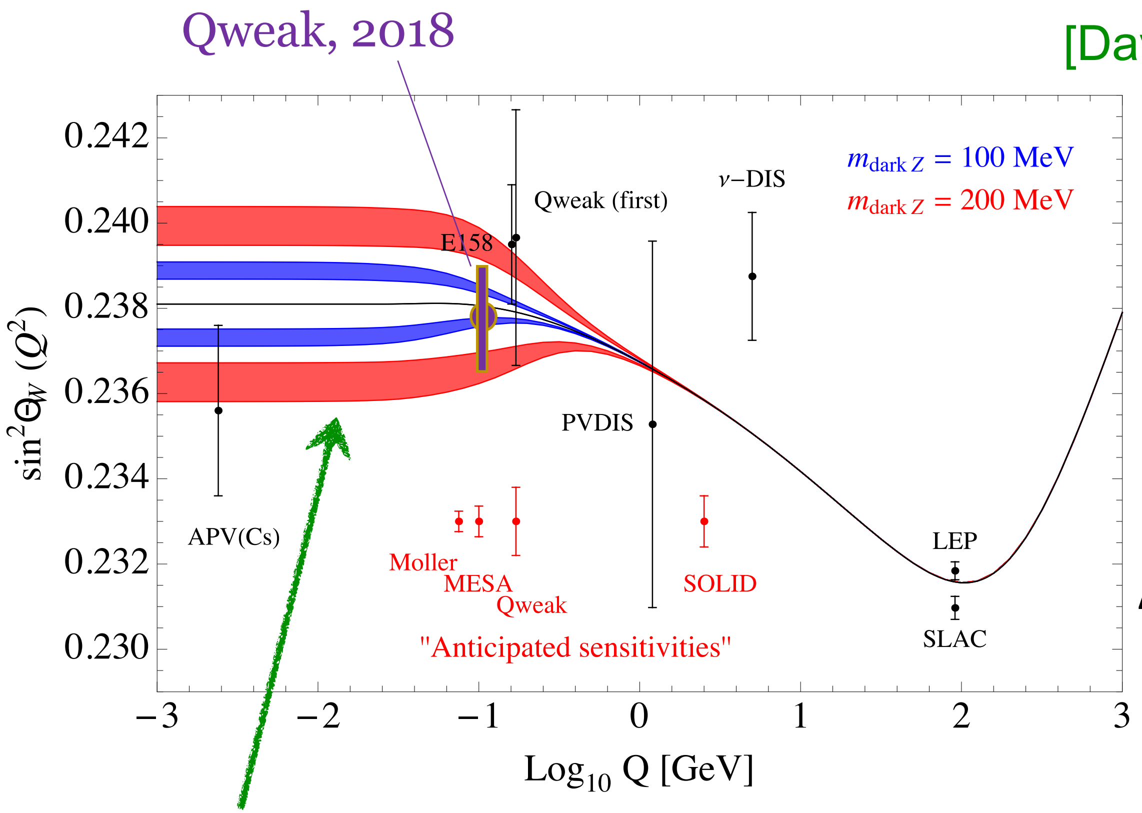

Note: $A_Z/A_\gamma \approx Q^2 \; for \; Q^2 \ll MZ;$
$: A_Z/A_\gamma \approx 1 \; for \; Q^2 \gg MZ$

*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***

**Phys.Lett. B712 (2012) 261-265**

# 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.

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

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 Q² 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*

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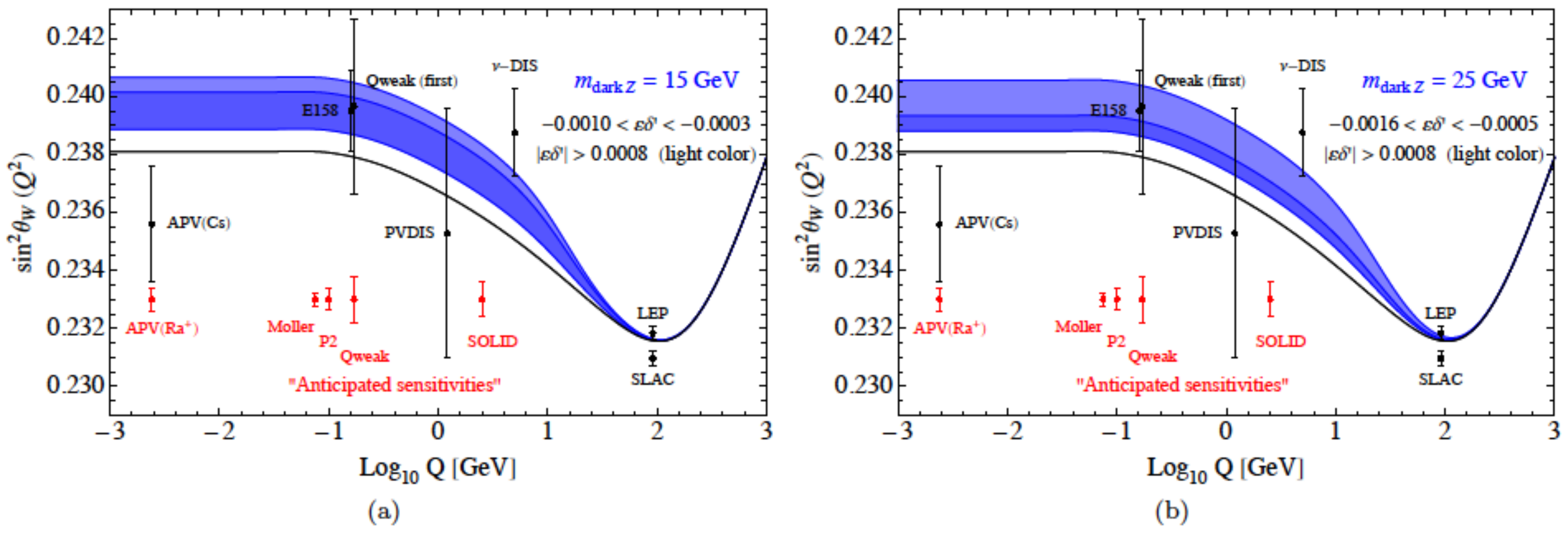
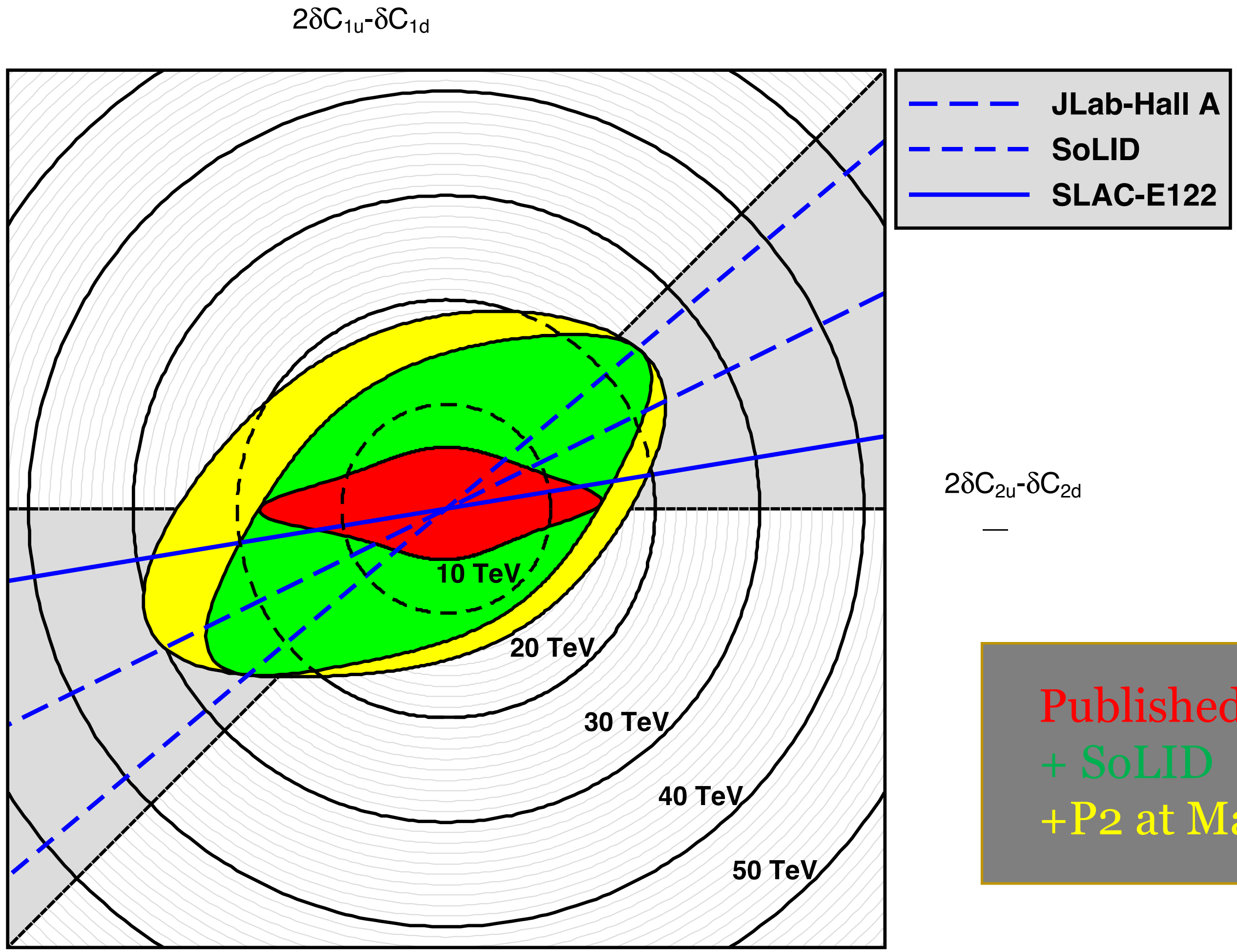



FIG. 3. Effective weak mixing angle running as a function of $Q^2$ shift (the blue band) due to an intermediate mass $Z_d$ for (a) $m_{Z_d} = 15$ GeV and (b) $m_{Z_d} = 25$ GeV for 1 sigma fit to $\varepsilon\delta'$ in Eq. (12). The lightly shaded area in each band corresponds to choice of parameters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

# Sensitivity to Λ in Composite Models (LHC)




Published data
+ SoLID
+P2 at Mainz

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

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

Credit: J. Erler

# An Example of a Dimension-8 Operator

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

# Charge Symmetry Violation

We already know CSV exists:

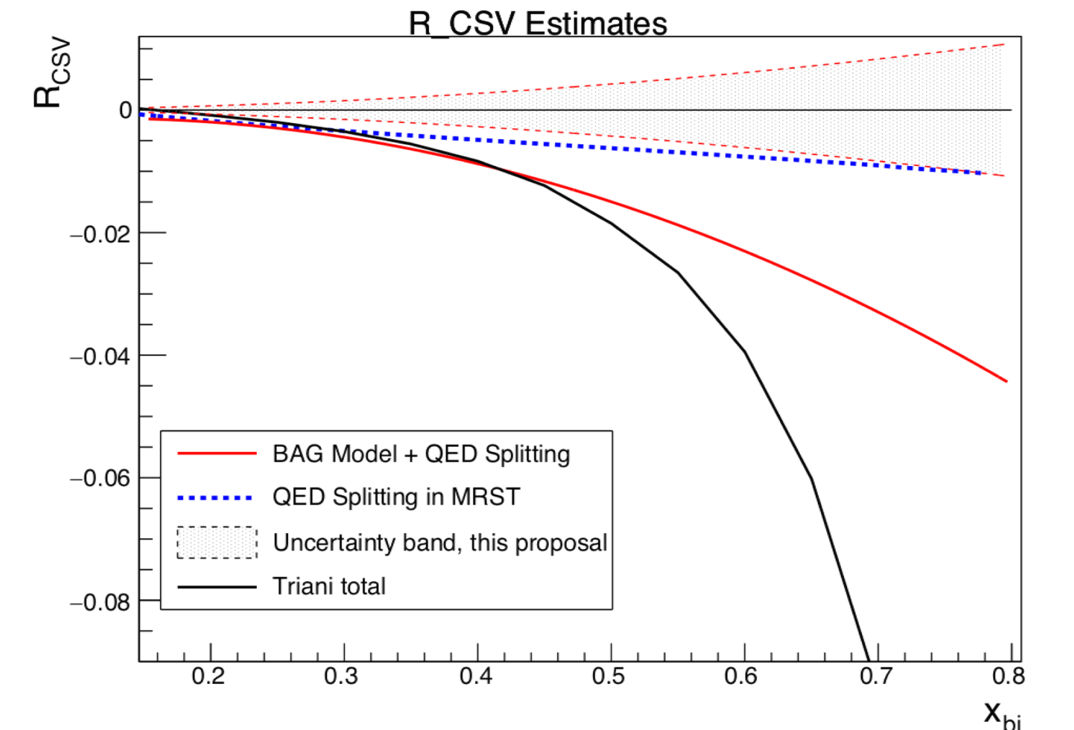
- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

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

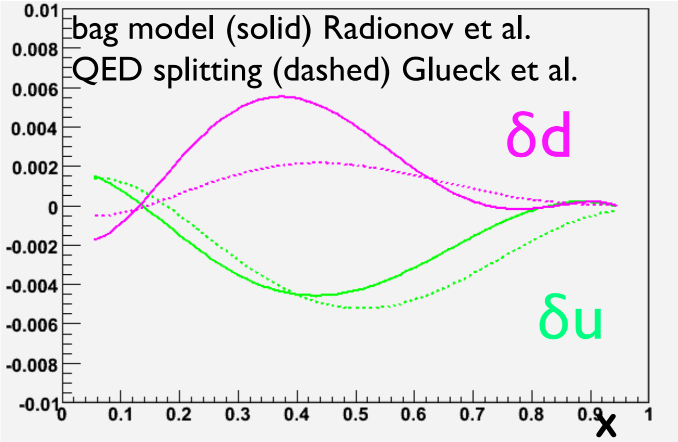
- Direct sensitivity to parton-level CSV
- Important implications for PDF's
- Could be partial explanation of the NuTeV anomaly

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

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



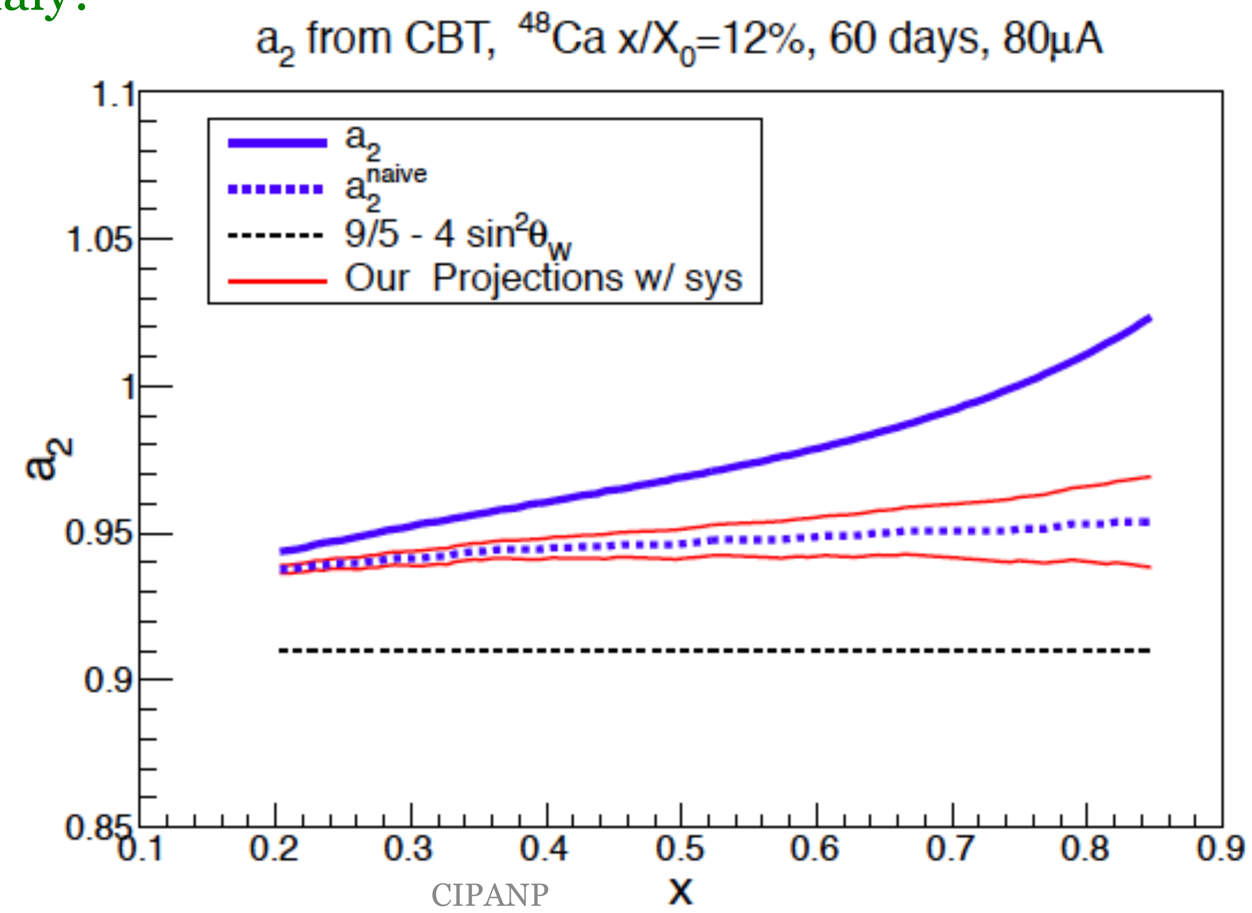

Sensitivity will be enhanced if u+d falls off more rapidly than δu-δd as x → 1




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

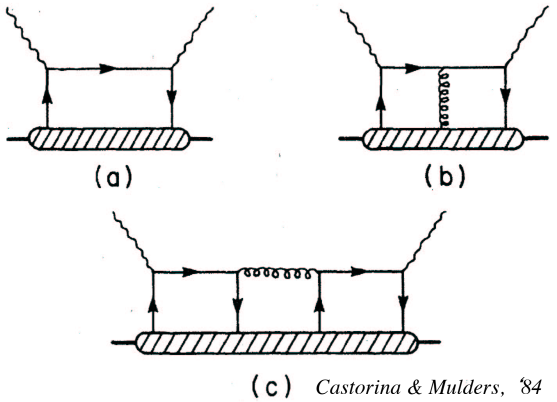
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y) b(x)\right]$$

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

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

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



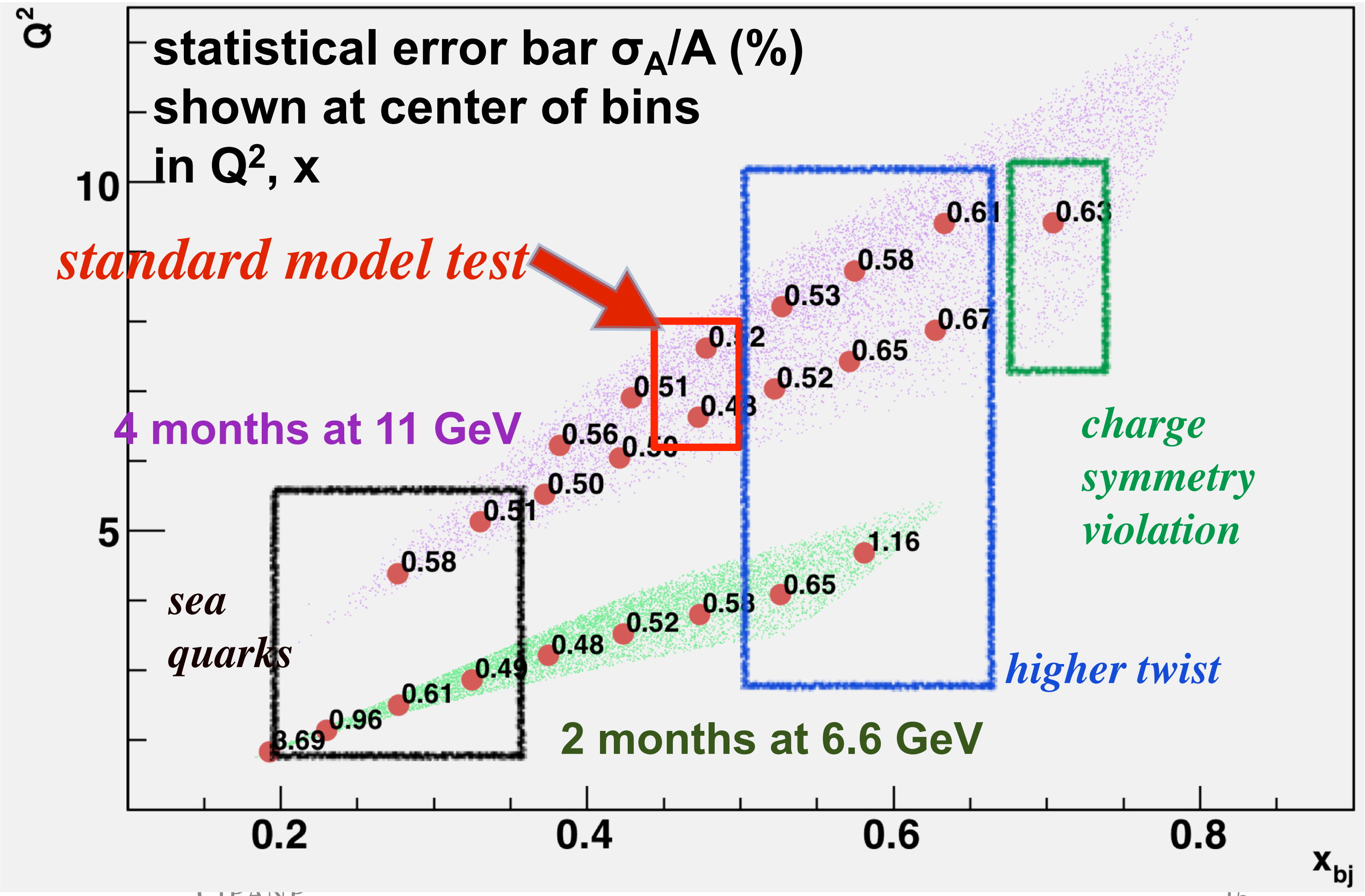
Castorina & Mulders, '84

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

$\sigma_L$ contributions cancel

Use ν data for small b(x) term.

# SoLID 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 |

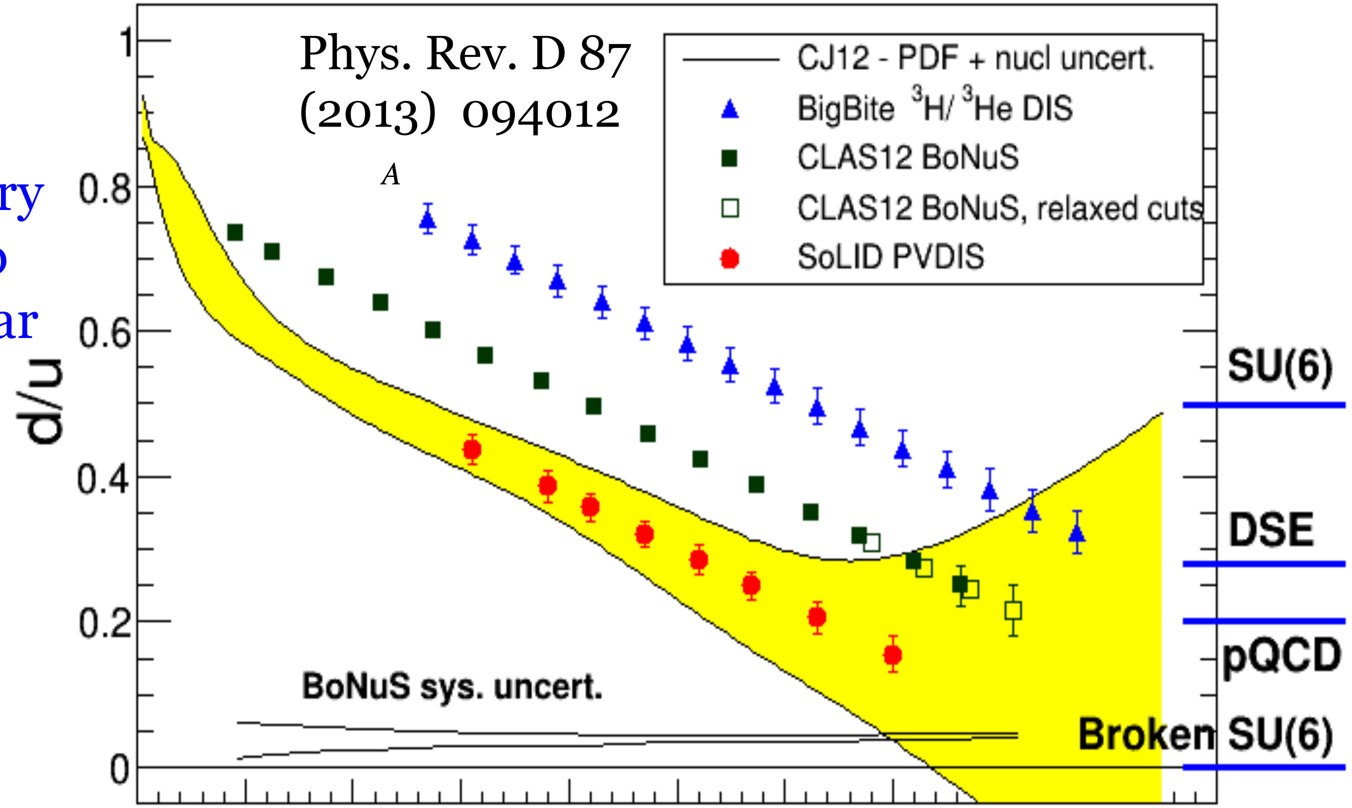
$$A_{\text{Meas.}} = A_{\text{SM}} \left[ 1 + \frac{\beta_{\text{HT}}}{(1-x)^3 Q^2} + \beta_{\text{CSV}} x^2 \right]$$

# PVIDS with the Proton

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

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

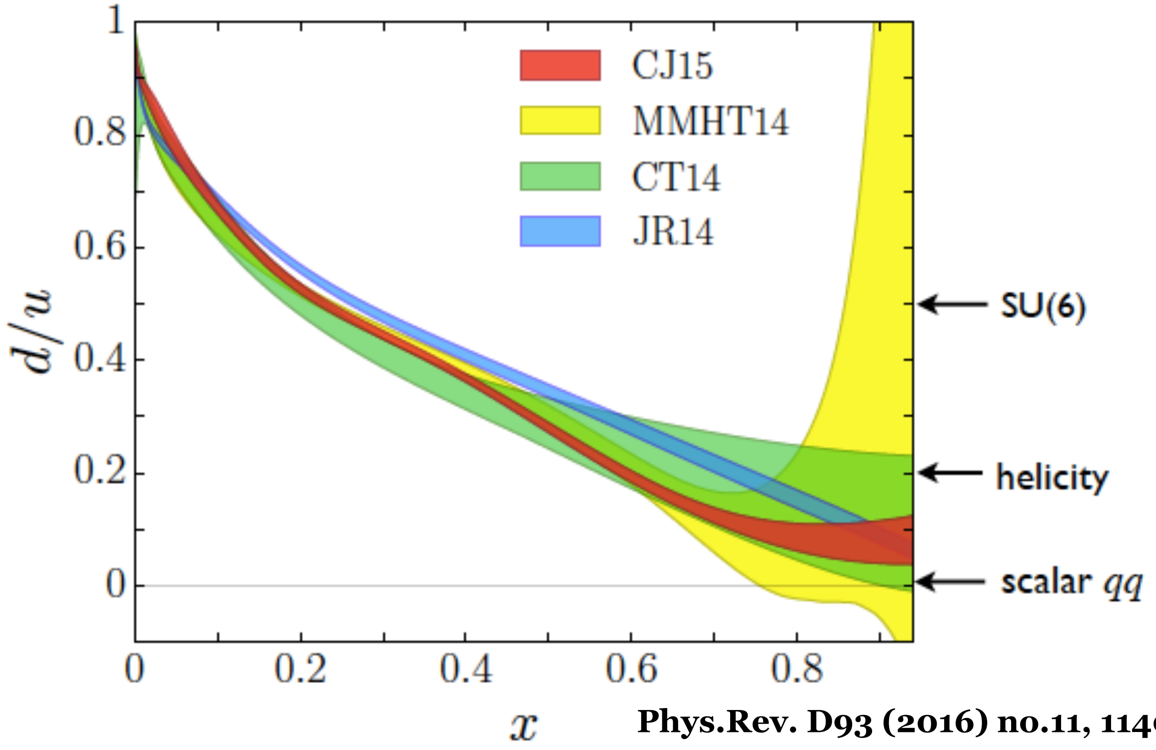
PVDIS is complementary to the rest of the JLAb d/u program: no nuclear effects



# Recent d/u Analysis Including 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.




Phys.Rev. D93 (2016) no.11, 114017

# SoLID Timeline

- 2017 Passed Director's Review
- 2018 DOE Science review
- 2020 CDO?
- 2025 Construction finished??

# Summary

- SoLID is a high luminosity, high acceptance spectrometer that can fully exploit the potential of the Jlab 12 GeV upgrade.
- Only PVDIS can measure C2's as BSM test.
- PVDIS provides unique window on hadronic physics.
  - Charge Symmetry Violation.
  - Isovector EMC effect.
  - Quark-quark correlations.
  - d/u without nuclear corrections.
- Anticipate DOE Science Review soon.

# Backups

# 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

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

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

# Lepton Pair Production Cross Sections

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

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

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

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

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 $\Lambda$.)

# Lorentz Invariance Violation

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

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

# Published 6 GeV PVDIS data from JLab

## 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$^2$**

| | |
|---|---|
| $A^{phys}$ (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

# 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.

# Lepton Pair Production form ATLAS

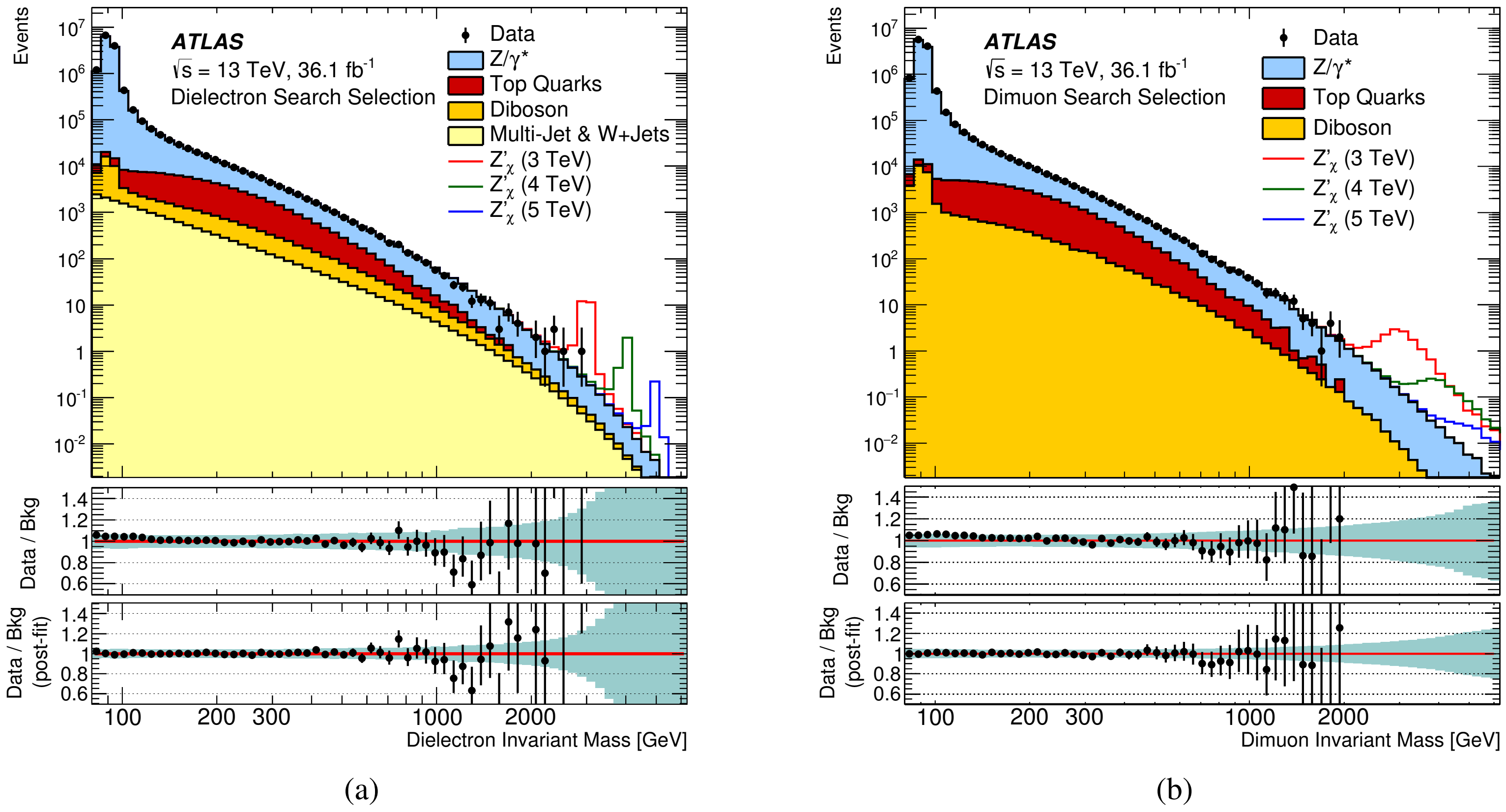



Figure 1: Distributions of (a) dielectron and (b) dimuon reconstructed invariant mass ($m_{\ell\ell}$) after selection, for data and the SM background estimates as well as their ratio before and after marginalisation. Selected $Z'_\chi$ signals with a pole mass of 3, 4 and 5 TeV are overlaid. The bin 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.