Update on PVDIS Motivation

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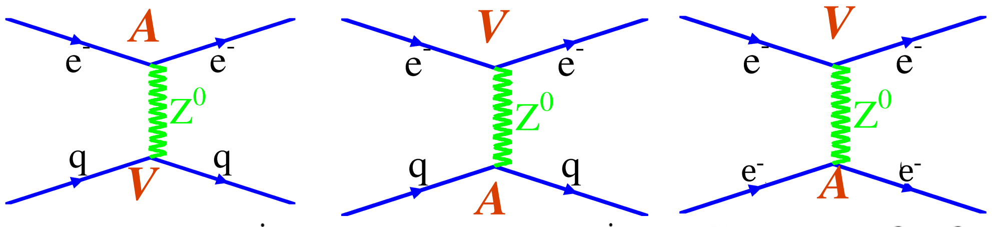
Outline

- Theory of PVDIA.
- SMEFT, C_{1q} and C_{2q} and PVDIS.
- PVDIS as a probe of hadronic structure.

PVES and Contact Interactions

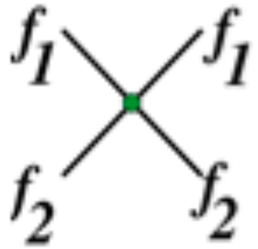


$C_{1i} \equiv 2 g_A^e g_V^i$ $\quad$ $C_{2i} \equiv 2 g_V^e g_A^i$ $\quad$ $C_{ee} = 2 g_V^e g_A^e$

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

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

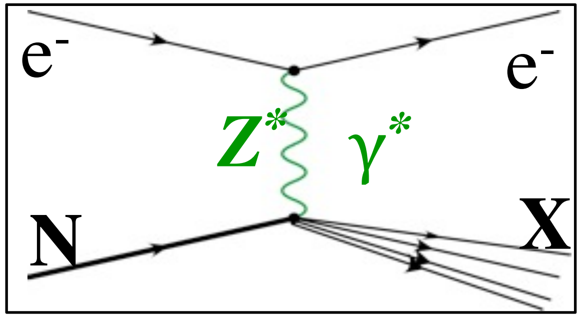
+ new physics



$$\mathcal{L}_{eff}^{BSM} = \frac{g^2}{\Lambda^2} \sum_{i,j=L,R} \eta_{ij}^{eff} \bar{e}_i\gamma_\mu e_i \bar{q}_j\gamma^\mu q_j$$

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

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

SMEFT to All Order

$$\mathcal{L} = \sum_d \sum_{ij} \frac{C_d^{ij}}{\Lambda^{4-d}} \mathcal{O}_d^{ij}$$

Wilson coefficient
(ie.coupling constants)

d = dimension
of the operator

$$\mathcal{O}_d^{ij} = \overline{e}_i \gamma_\mu e_i \overline{f}_j \gamma^\mu f_j$$

$$e_{L/R} = \frac{1}{2}(1 \mp \gamma^5)\psi_e$$

e = electron spinor
f = quark spinor

$$\mathcal{O}_d^{ij} = LL_f,\ LR_f,\ RL_f,\ RR_f$$

LL_f is shorthand

Most common for SMEFT

Couplings: Warsaw Basis

$$C_{lq}^{(3)}:\ \frac{1}{2}(LL_u - LL_d);\quad C_{lq}=C_{lq}^{(1)}:\ \frac{1}{2}(LL_u + LL_d)$$

$$C_{lu}:\ LR_u;\quad C_{ld}:\ LR_d;\quad C_{eu}:\ RR_u;$$

$$C_{ed}:\ RR_d;\quad C_{eq}:\ RL_u + RL_d$$

61 d=6; 993 d=8 independent couplings

$$g_{AV}^{eu} = \frac{1}{2}[C_{lq}^{(3)} - C_{lq} - C_{eu} + C_{eq} + C_{eu}]$$

$$g_{VA}^{eu} = \frac{1}{2}[C_{lq}^{(3)} - C_{lq} + C_{eu} - C_{eq} + C_{eu}]$$

Go to PVES Basis

$$VV = +LL + LR + RL + RR$$

$$VA = -LL + LR - RL + RR$$

$$AV = -LL - LR + RL + RR$$

$$AA = +LL - LR - RL + RR$$

C_2's

Physical Processes

$$\mathcal{A} = (\mathcal{A}_{SM} + \frac{\mathcal{A}_6}{\Lambda^2} + \frac{\mathcal{A}_8}{\Lambda^4} \ldots)$$

$$\text{For PVES}: \quad A_{PV} \sim \mathcal{A}_{EM} \times \mathcal{A}$$

$$\text{For Drell} - \text{Yan}: \quad \sigma_{BSM} \sim (\mathcal{A}_6)^2 + \mathcal{A}_{SM} \times \mathcal{A}_8$$

PVES (interference effect) is only sensitive to d=6: $1/\Lambda^2$.
LHC (large s) sees d=6 but is dominated by $1/\Lambda^4$.

LHC Drell-Yan Analysis

$$\mathcal{L}_{eff} = \frac{g^2}{\Lambda^2} \sum_{i,j=L,R} \eta_{ij}^f \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j$$

$$g^2 = 4\pi; \quad \text{The largest } |\eta_{ij}^f| = 1$$

$$\text{Only dimension} - 6 \text{ operators}$$

$$\text{Choose } \eta_{ij}^f; \quad \text{Fit to } \Lambda$$

$$\text{Better : set } \sum (\eta_{ij}^f)^2 = 1$$

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 ~ $1/\Lambda^4$

(Both d=6 and d=8)

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:

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

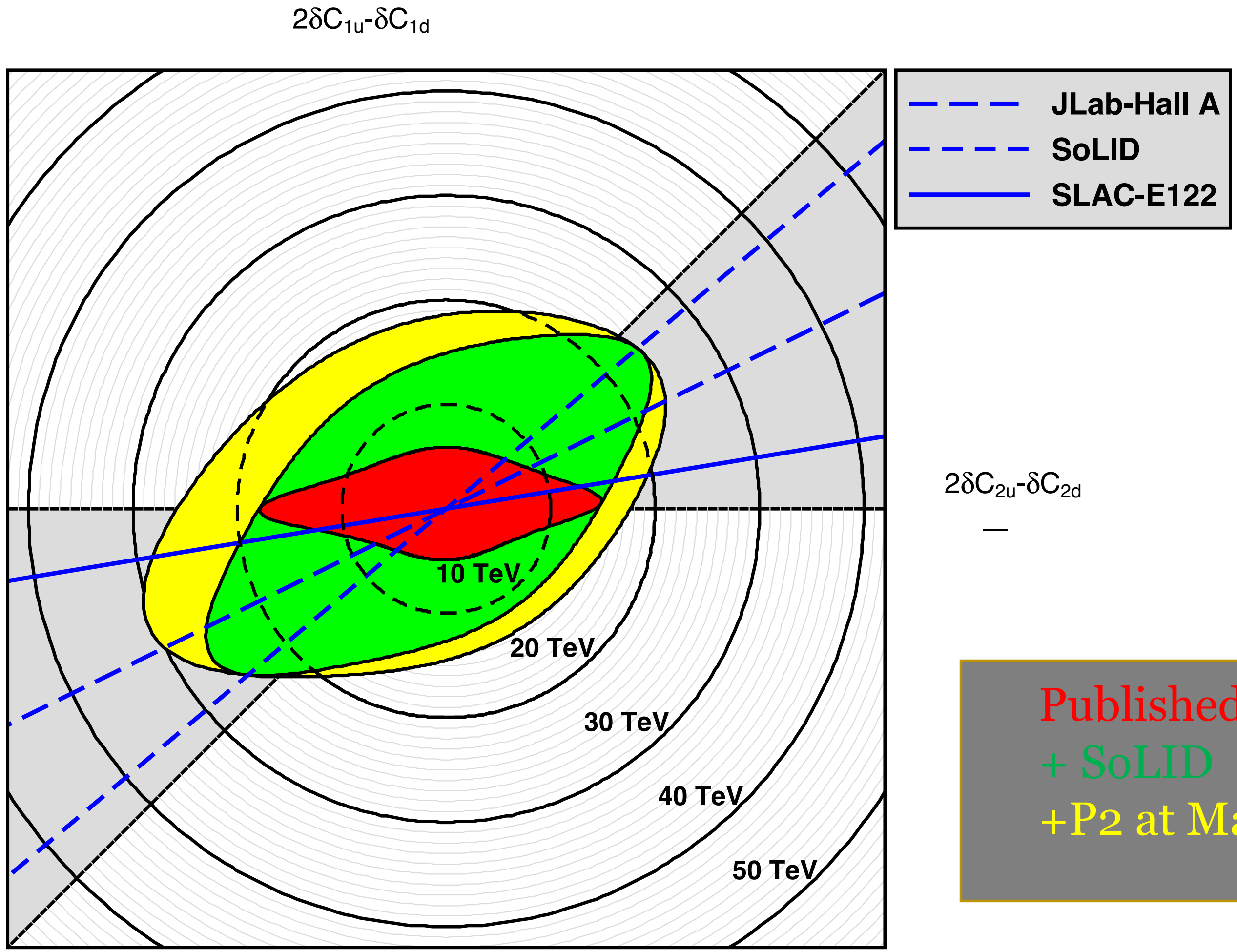
Convert from LR terms
To VA terms:

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

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 if d=8 neglected
(LHC experiments fit only to a single Λ.)

Sensitivity to Λ in Composite Models (LHC)



Published data
+ SoLID
+P2 at Mainz

C_{1q} known from APV, Qweak, and P2

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

Lepton Pair Production form ATLAS

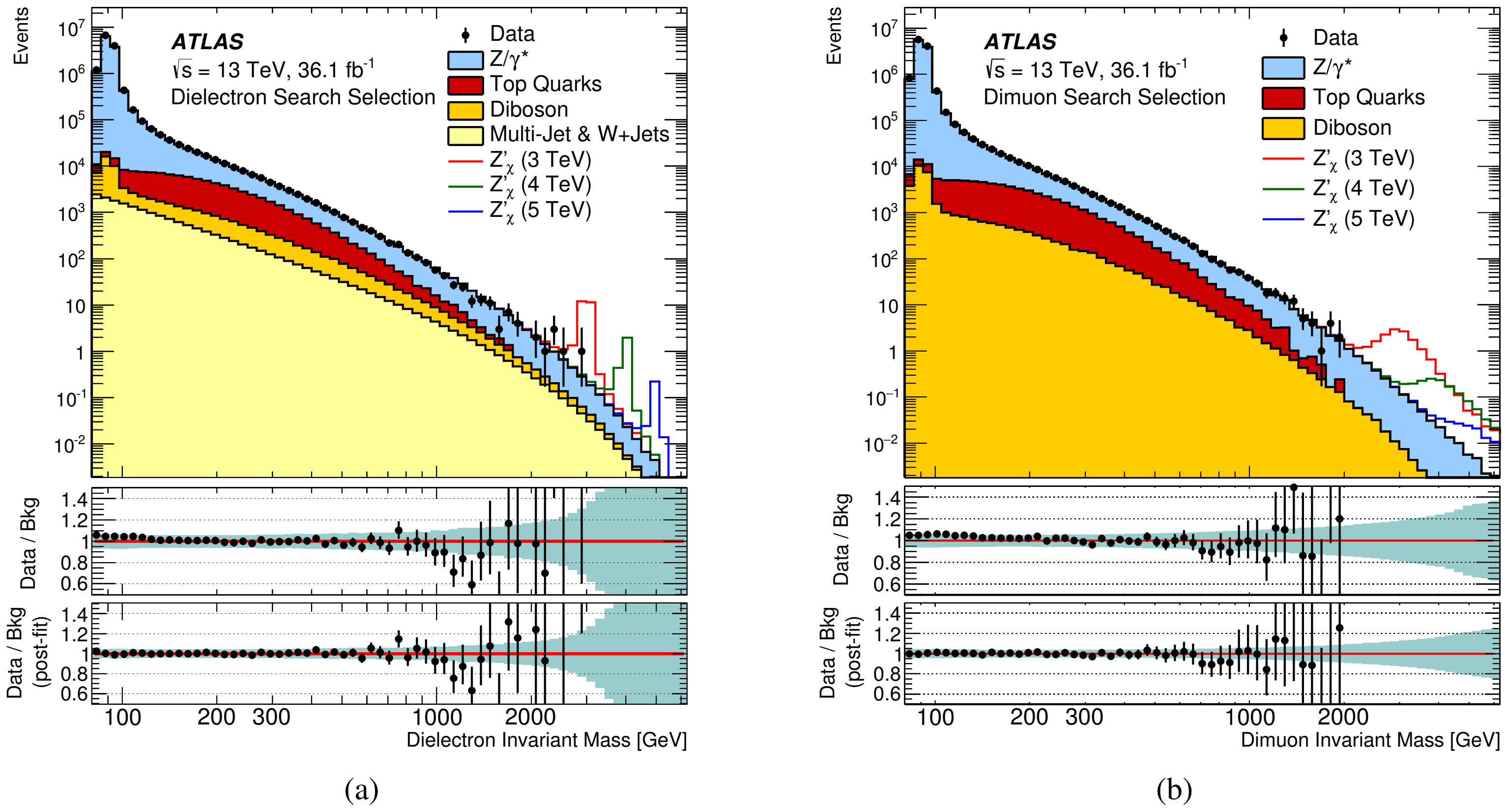
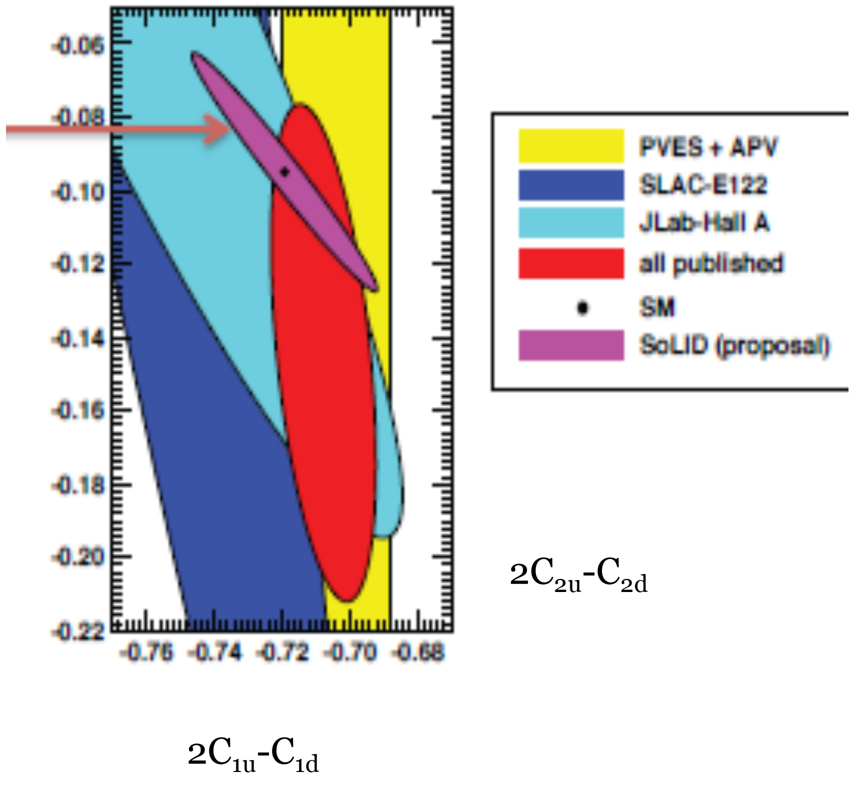


Figure 1: Distributions of (a) dielectron and (b) dimuon reconstructed invariant mass ($m_{\ell\ell}$) after selection, for data and the SM background estimates as well as their ratio before and after marginalisation. Selected Z'_χ signals with a pole mass of 3, 4 and 5 TeV are overlaid. The bin width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

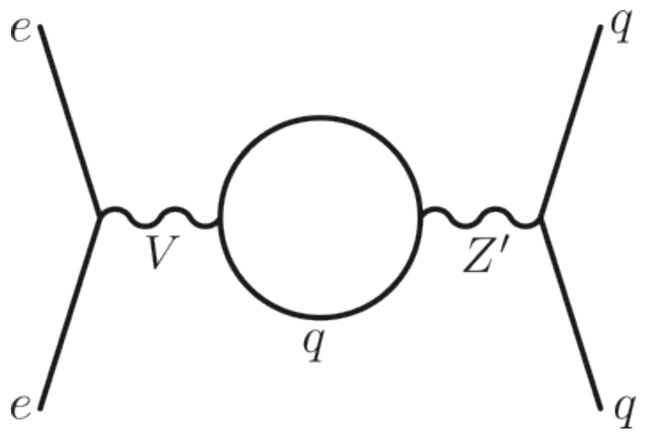
SoLID and the Low Energy PVES Program

- 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.



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***

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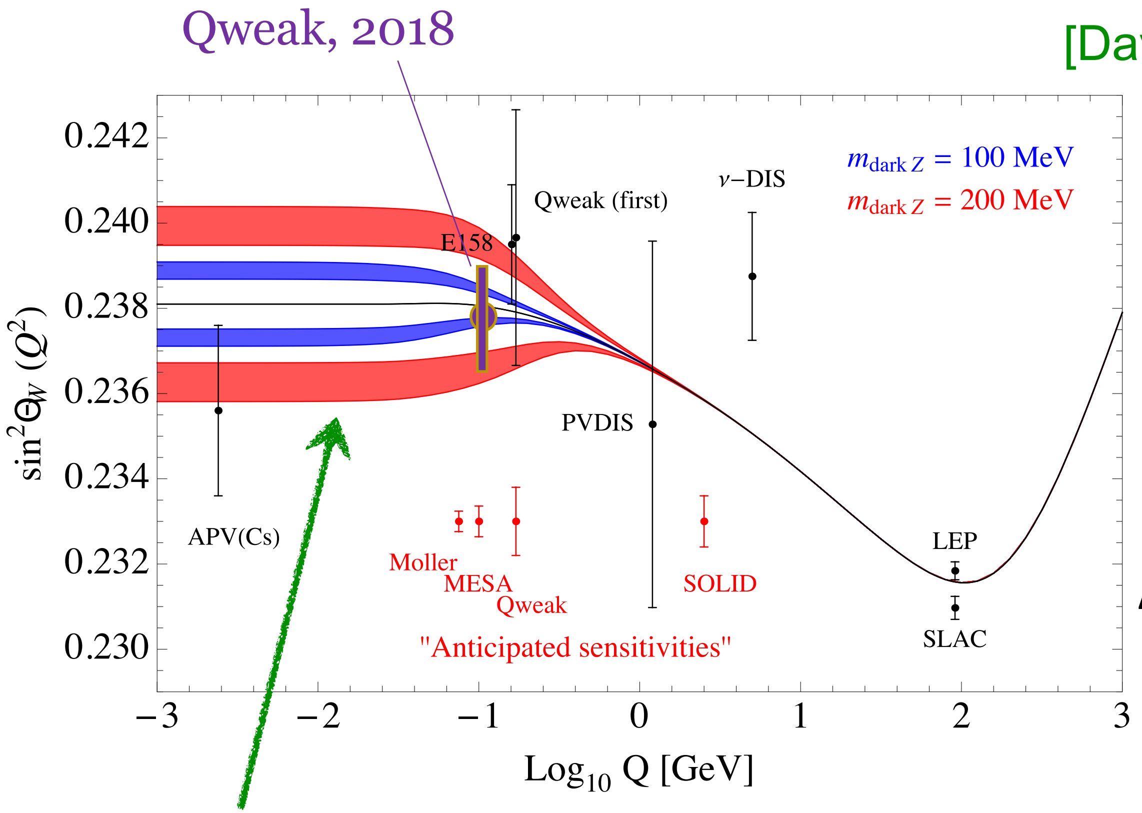
Weak angle shift for Low Q^2 due to Dark Z′

[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 Q² Range

Qweak data provides
Important limit.

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

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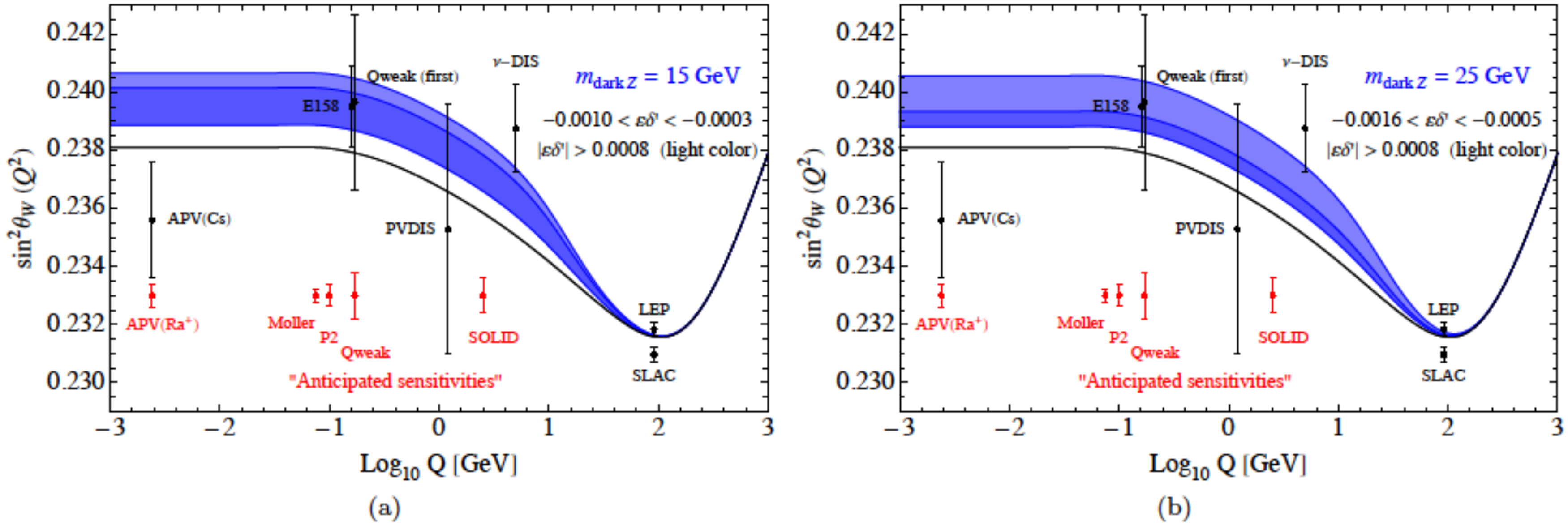


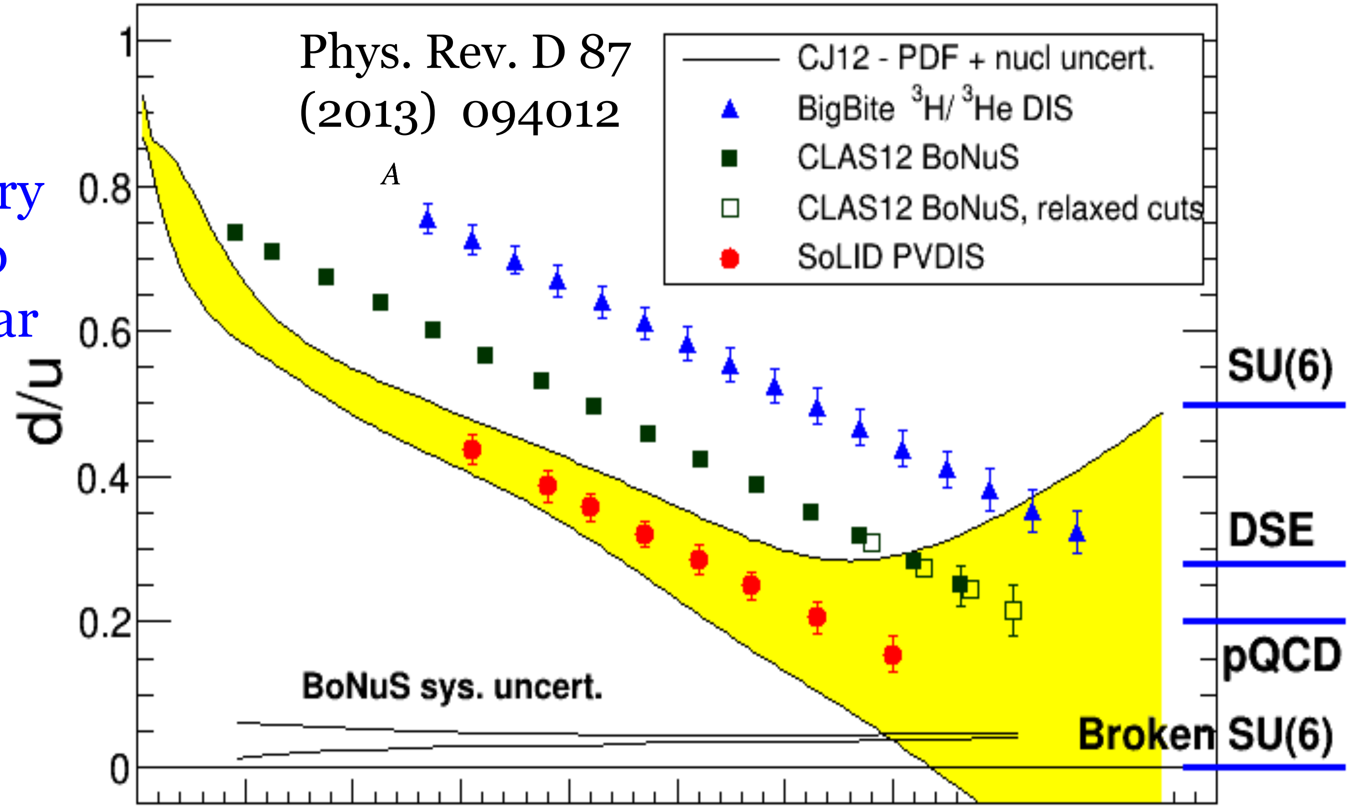
FIG. 3. Effective weak mixing angle running as a function of Q^2 shift (the blue band) due to an intermediate mass Z_d for (a) $m_{Z_d} = 15$ GeV and (b) $m_{Z_d} = 25$ GeV for 1 sigma fit to $\varepsilon\delta'$ in Eq. (12). The lightly shaded area in each band corresponds to choice of parameters that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

PVIDS with the Proton

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

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

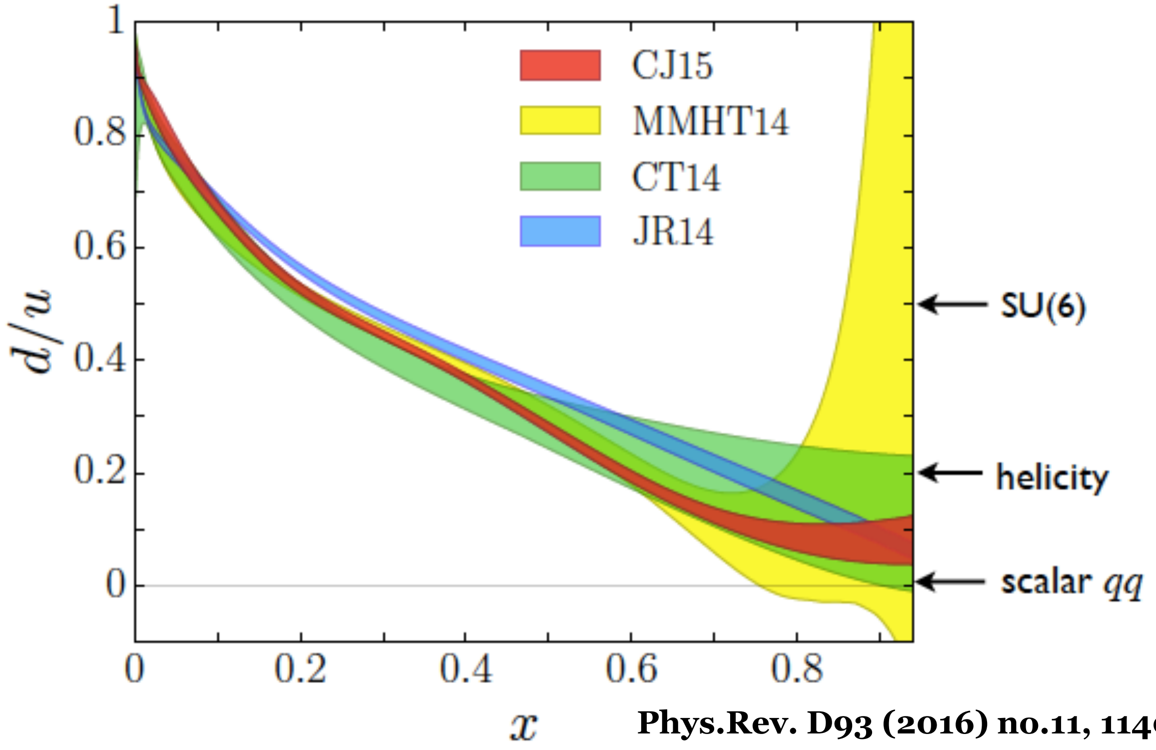
PVDIS is complementary to the rest of the JLAb d/u program: no nuclear effects



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.



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Summary

- SMEFT is main motivation, now and then.
- LHC Drell-Yan dominated by terms of order $1/\Lambda^4$
- Leptophobic Z's are of interest at the LHC.
- d/u more interesting.