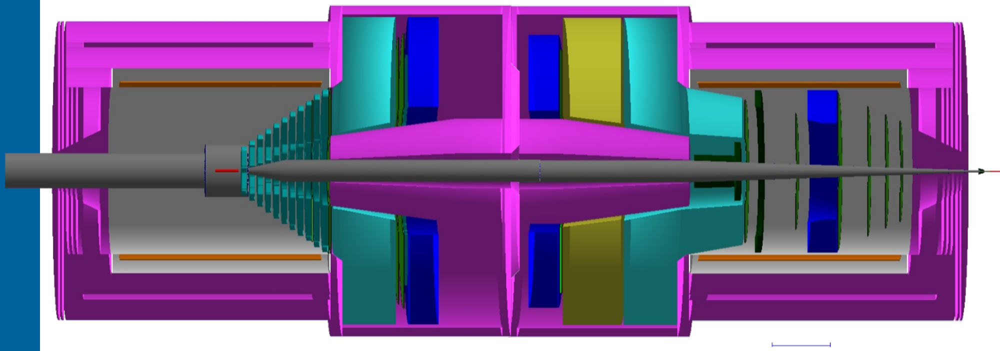
Parity Violation with SoLID: PVDIS & PVEMC



Paul E Reimer

30 June 2023
JLab, Newport News, VA

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Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

This work was partially supported under grant DE-AC02-06CH11357 from the US Department of Energy, Office of Nuclear Physics

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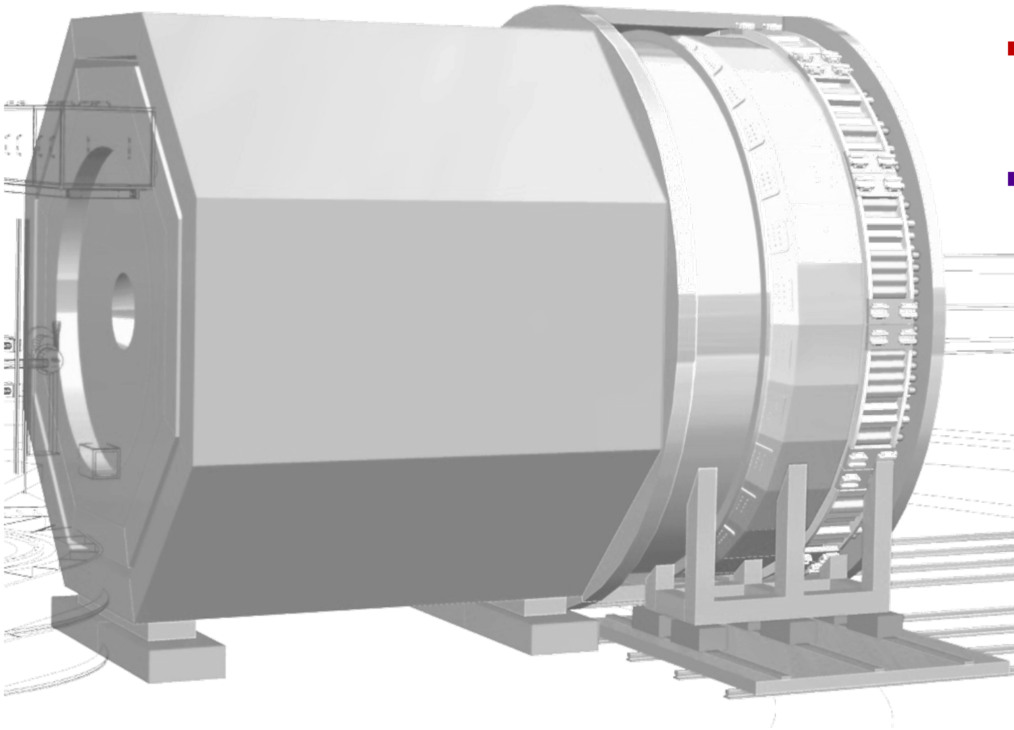
SoLID SOLENOIDAL LARGE INTENSITY DEVICE

SoLID – The Next-Gen Spectrometer at JLab



- Solid
  Solenoidal Large Intensity Device
- Rich physics program including
  – SIDIS
  – J/ψ production
  – **Parity Violation**

For an overview, see Xiaochao Zheng's talk at the JLab User's Meeting

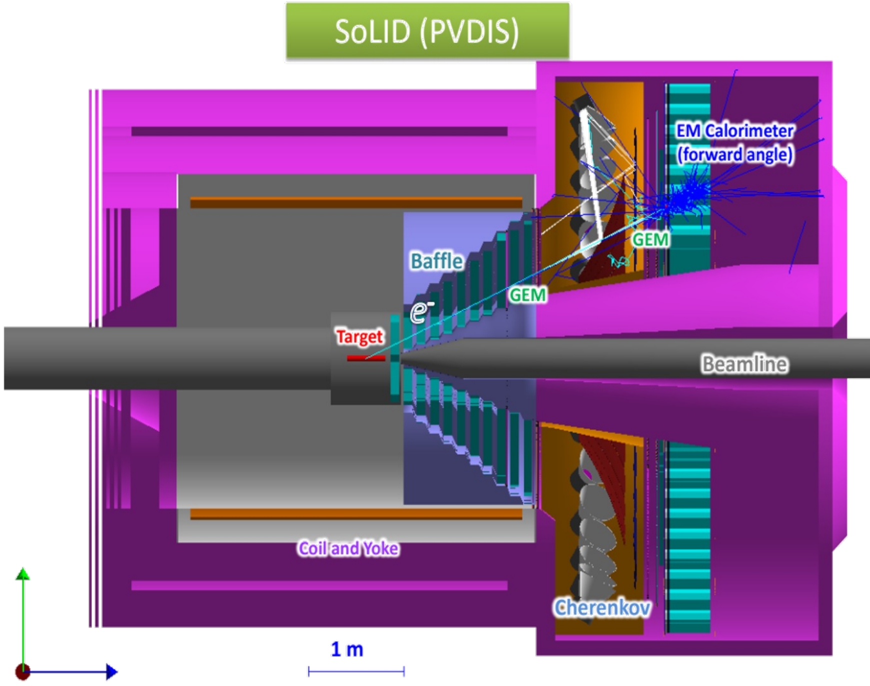
SoLID Apparatus for PVDIS

What do you need for to measure parity violation in DIS?

- DIS experiment: W^2 > 4 GeV^2 Isolate DIS events. Only electron is detected.
- PV experiment: High Luminosity with E ~ 11 GeV, stable systematics

What do you need to address the physics?

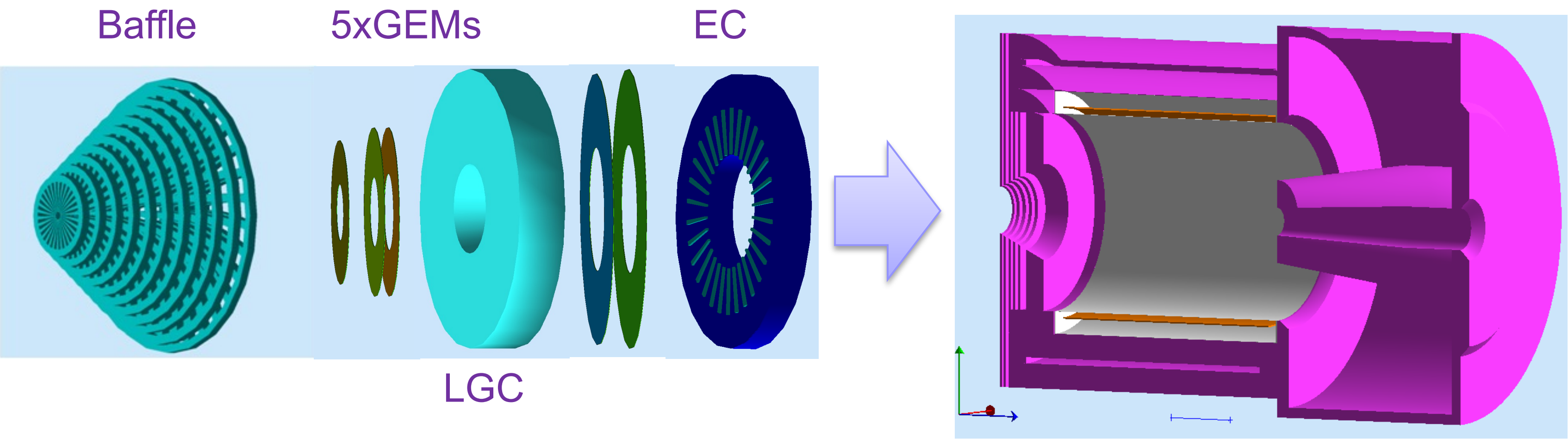
- Wide x-range: 0.25-0.75:
  - untangle physics.
  - Large scattering angles ~22°<θ<~35°
- Large azimuthal acceptance.
- Better than 1% statistical errors for small bins



- Large Q^2 range: Measure Higher Twist.
- 2 GeV < E'< 6 GeV: Low background
- Around 2% Momentum resolution

SoLID Apparatus

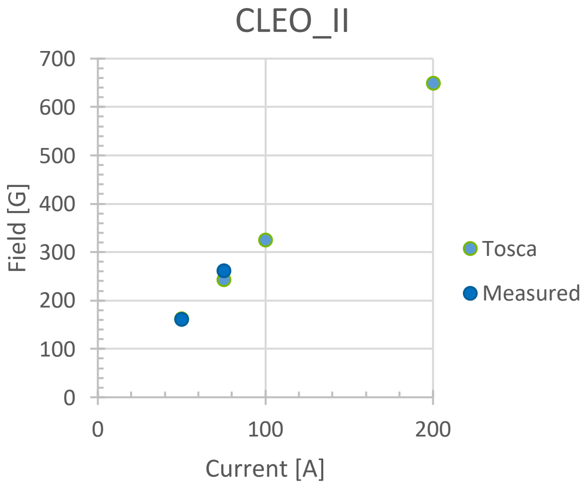
- Baffles to reject wrong momentum background
- Light Gas Cerekkov: identify electrons for trigger; reject pions.
- Shashlyk electromagnetic calorimeter (Ecal) : coincident trigger and further particle identification.
- With tracking, tight E/p cuts reduce pion backgrounds.

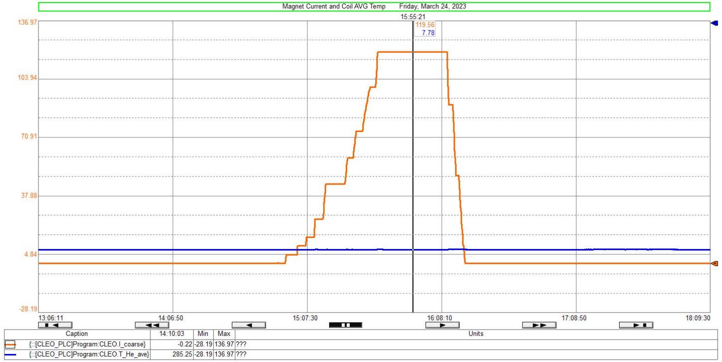


LATEST – CLEO-II MAGNET COLD TEST AT JLAB

Latest – CLEO-II Magnet Cold Test at JLab

- A low current test on March 24th.
- 3-axis Hall probe data matched TOSCA model well.
- Coil average temperature remained constant during test.
- Success!!





content from W. Seay and X. Zheng

Parity NonConservation and Electron Scattering

LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

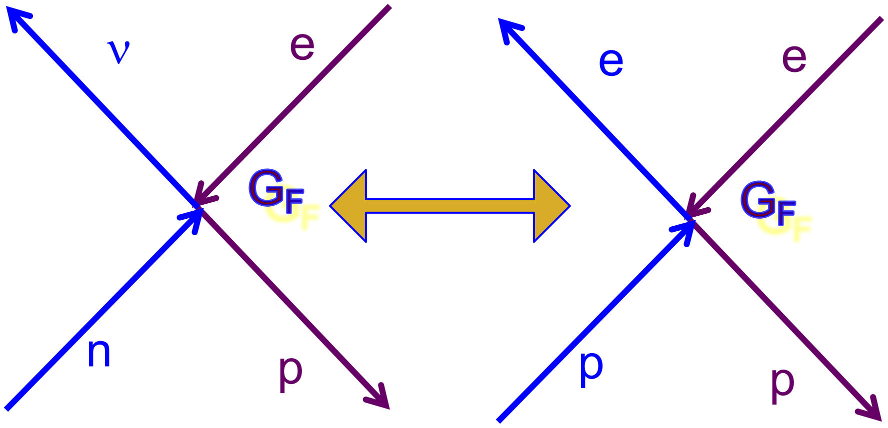
Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964-966 (March, 1959)

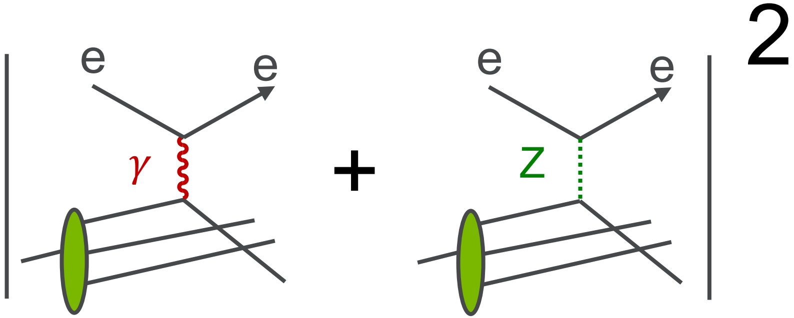
Proposes that electron scattering should have measurable parity violating asymmetry

- Proposes interaction like that responsible for β decay to occur in electron scattering
- Argues cross sections for scattering left- and right-handed electrons *could* differ



ZEL'DOVICH

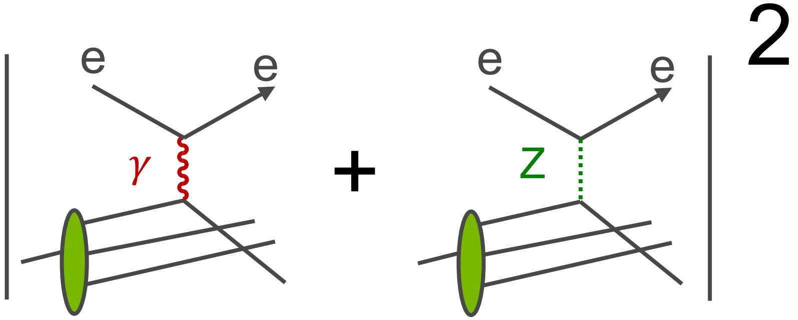
$\sigma =$



$$\sigma^l \propto \left|\mathcal{M}_{\text{em}} + \mathcal{M}^l_{\text{weak}}\right|^2 \qquad \sigma^r \propto \left|\mathcal{M}_{\text{em}} + \mathcal{M}^r_{\text{weak}}\right|^2$$

$$\approx \left|\mathcal{M}_{\text{em}}\right|^2 + 2\mathcal{M}_{\text{em}}\mathcal{M}^l_{\text{weak}} + \left|\mathcal{M}^l_{\text{weak}}\right|^2$$

ZEL'DOVICH

$\sigma =$ 

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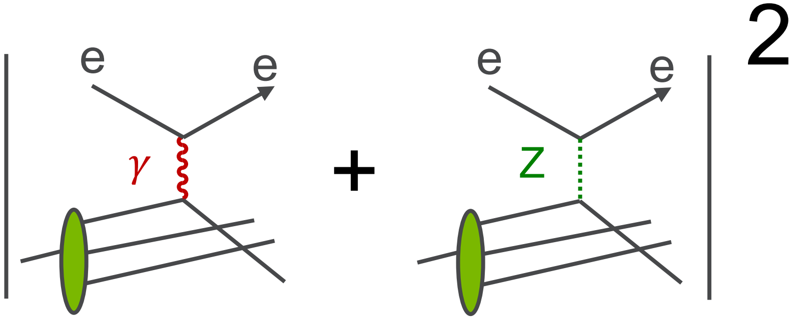
$$\approx \left|\mathcal{M}_{\text{em}}\right|^2 + 2\mathcal{M}_{\text{em}}\mathcal{M}^l_{\text{weak}} + \left|\mathcal{M}^l_{\text{weak}}\right|^2$$

Large, but equal

Tiny

ZEL'DOVICH

$\sigma =$



$$\sigma^l \propto |\mathcal{M}_{\text{em}} + \mathcal{M}^l_{\text{weak}}|^2 \qquad \sigma^r \propto |\mathcal{M}_{\text{em}} + \mathcal{M}^r_{\text{weak}}|^2$$

$$\approx |\mathcal{M}_{\text{em}}|^2 + 2\mathcal{M}_{\text{em}}\mathcal{M}^l_{\text{weak}} + |\mathcal{M}^l_{\text{weak}}|^2$$

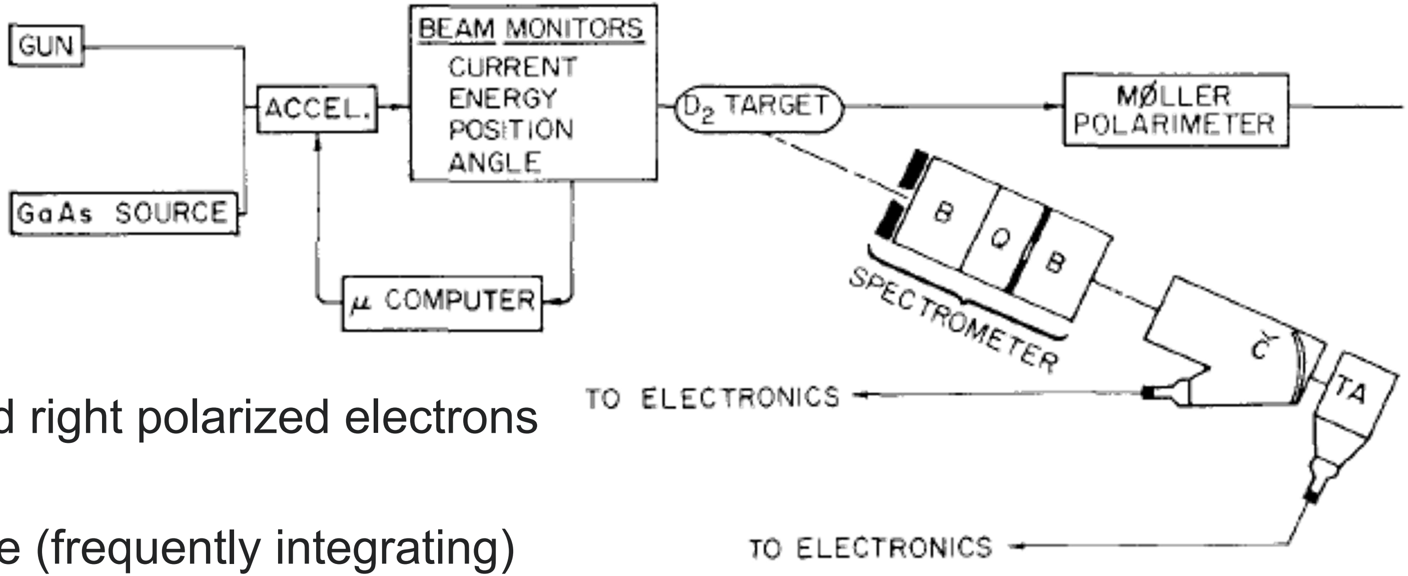
$$A_{\text{PV}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r}$$

$$\approx \frac{\mathcal{M}^l_{\text{weak}} - \mathcal{M}^r_{\text{weak}}}{\mathcal{M}_{\text{EM}}}$$

Large, but equal

Tiny

SLAC E-122



Prescott et al SLAC E-122

- Scatter left and right polarized electrons from target
- Count/measure (frequently integrating) number scattered into specific solid angle
- **Keep systematic effects in control**
- Form asymmetry and publish

1ST GENERATION PV EXPERIMENT IN 1977

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING ☆

C.Y. PRESCOTT, W.B. ATWOOD, R.L.A. COTTRELL, H. DeSTAEBLER, Edward L. GARWIN, A. GONIDEC [1], R.H. MILLER, L.S. ROCHESTER, T. SATO [2], D.J. SHERDEN, C.K. SINCLAIR, S. STEIN and R.E. TAYLOR
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

J.E. CLENDENIN, V.W. HUGHES, N. SASAO [3] and K.P. SCHÜLER
Yale University, New Haven, CT 06520, USA

M.G. BORGHINI
CERN, Geneva, Switzerland

Phys. Lett. 77B, 347 (1979)

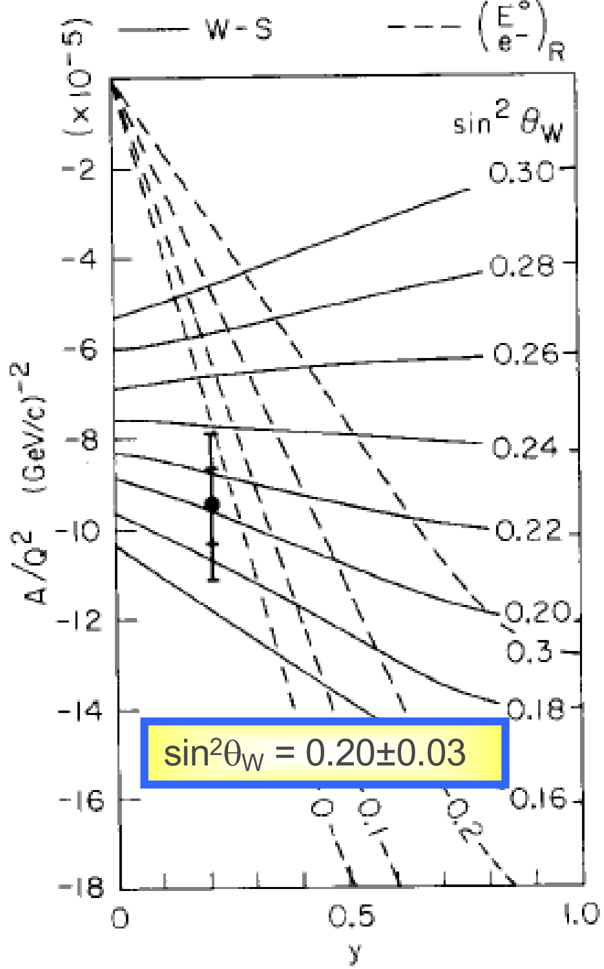
K. LÜBELSMEYER
Technische Hochschule Aachen, Aachen, West Germany

and

W. JENTSCHKE
II. Institut für Experimentalphysik, Universität Hamburg, Hamburg, West Germany

Received 14 July 1978

Abstract
We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6$ $(GeV/c)^2$ the asymmetry is $(-9.5\times10^{-5})Q^2$ with statistical and systematic **uncertainties each about 10%**



This experiment convinced the world that the Z-boson violated parity.

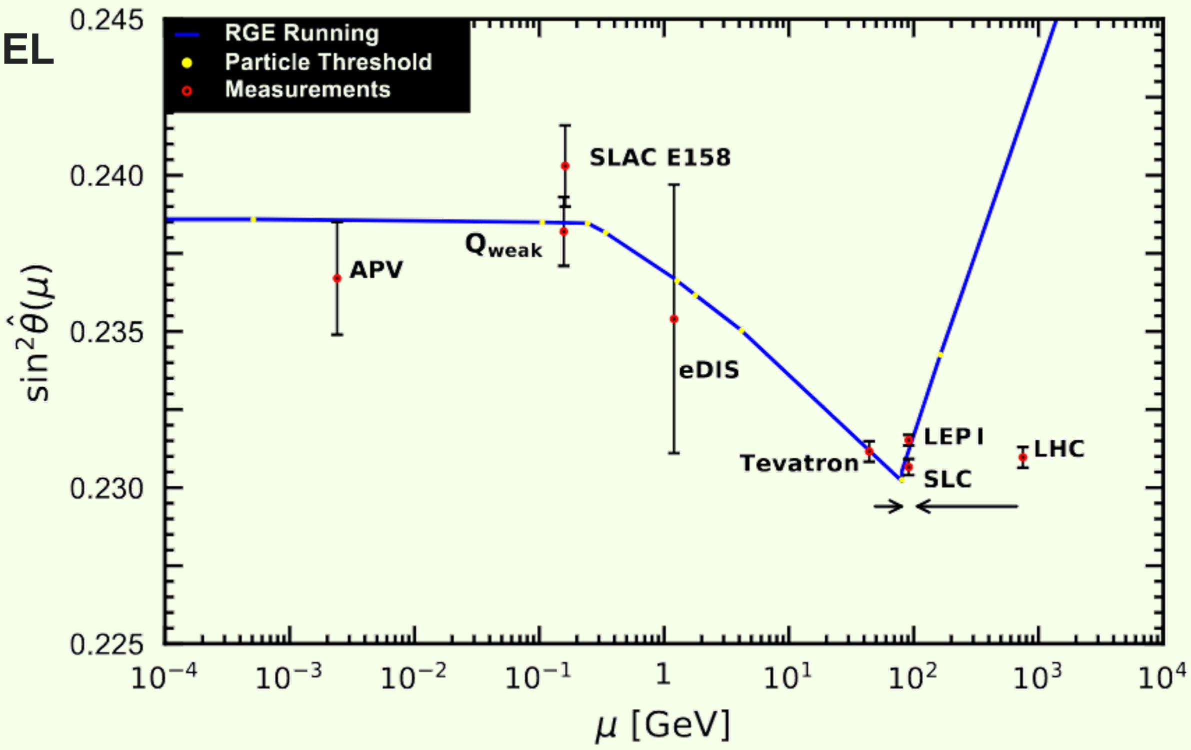
Probing the Standard Model

What we know:

- The Standard Model is extremely accurate
  – annoyingly so in some cases.
- But there are slight disagreements

What we don't know:

- Exactly what is missing



PVDIS VARIABLES

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

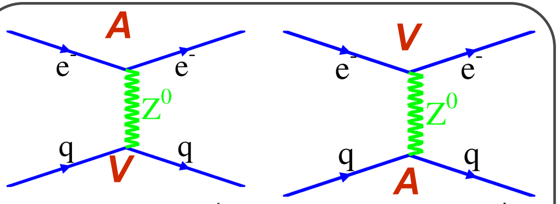
$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

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

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

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

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



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

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

QCD

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

PVDIS Variables

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

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

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

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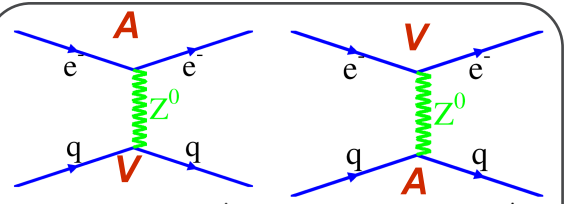

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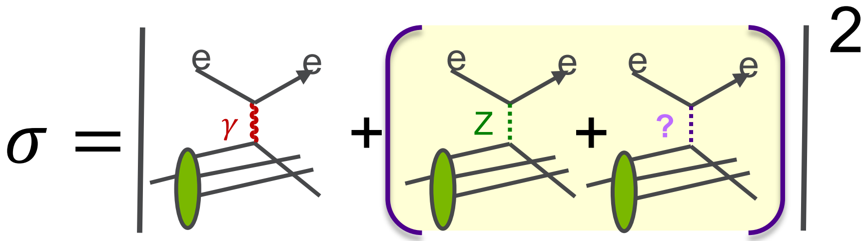
Half full or half empty

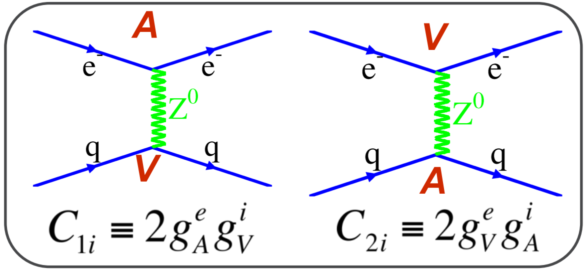
QCD

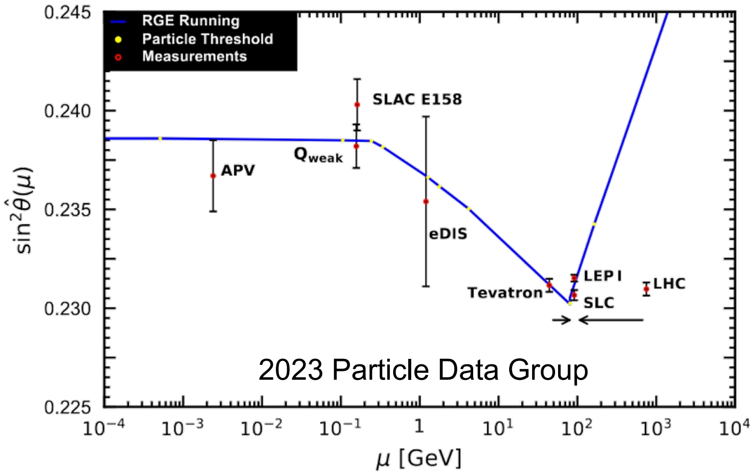
- Parton distributions (u, d, s, c)
- Charge Symmetry (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)

PARITY VIOLATION AS A TOOL TO INVESTIGATE THE STANDARD MODEL



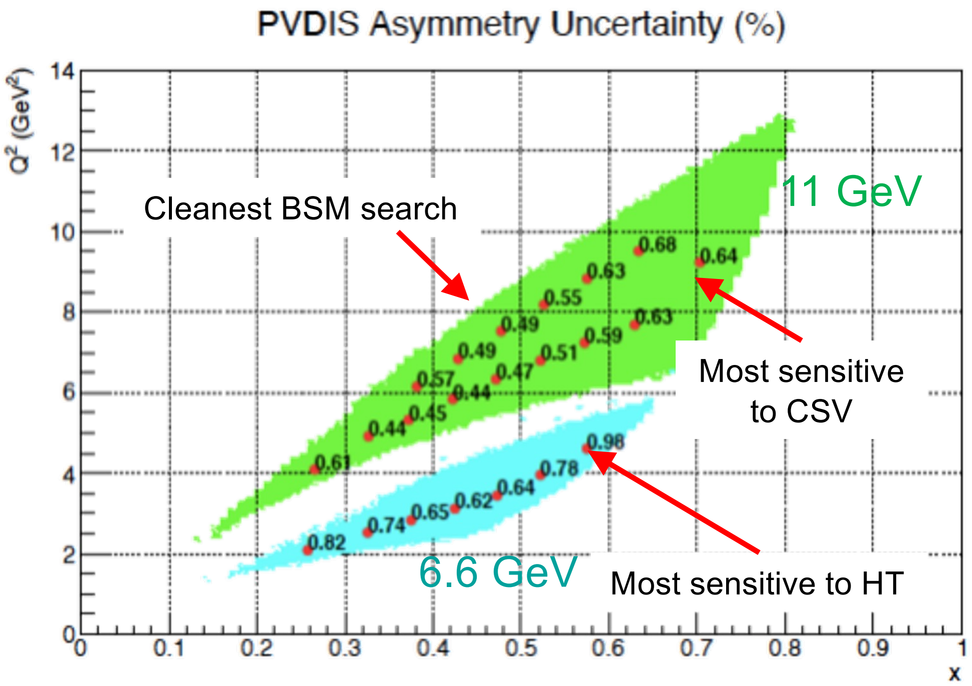
$$A_{\mathrm{PV}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{\mathrm{weak+BSM}} - \mathcal{M}^r_{\mathrm{weak+BSM}}}{\mathcal{M}_{\mathrm{EM}}}$$





- $\sin^2\theta_W$ is a Standard Model Parameter
- Search for NSM Physics looks directly at **couplings**

Extracting the Physics



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

Half full or half empty

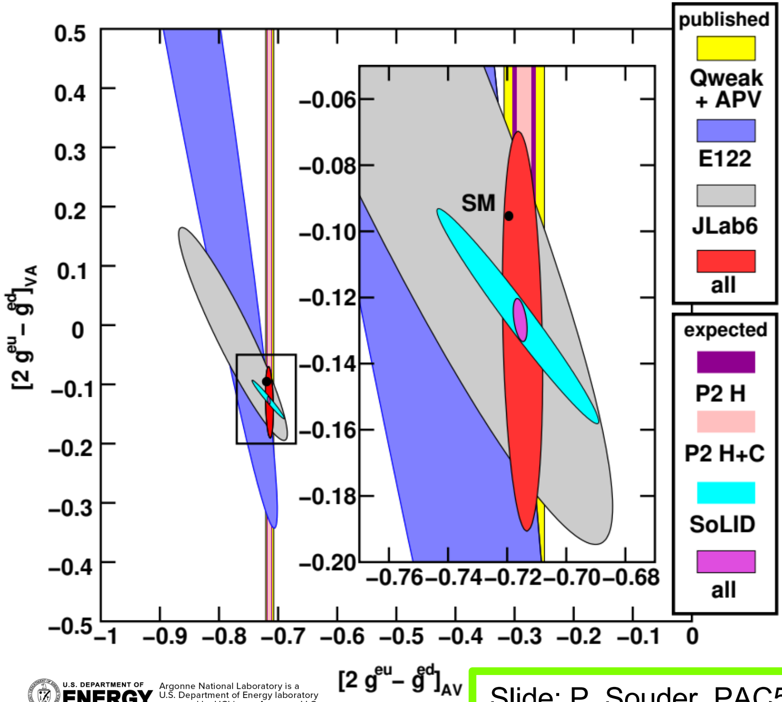
Kinematic dependence of physics topics:

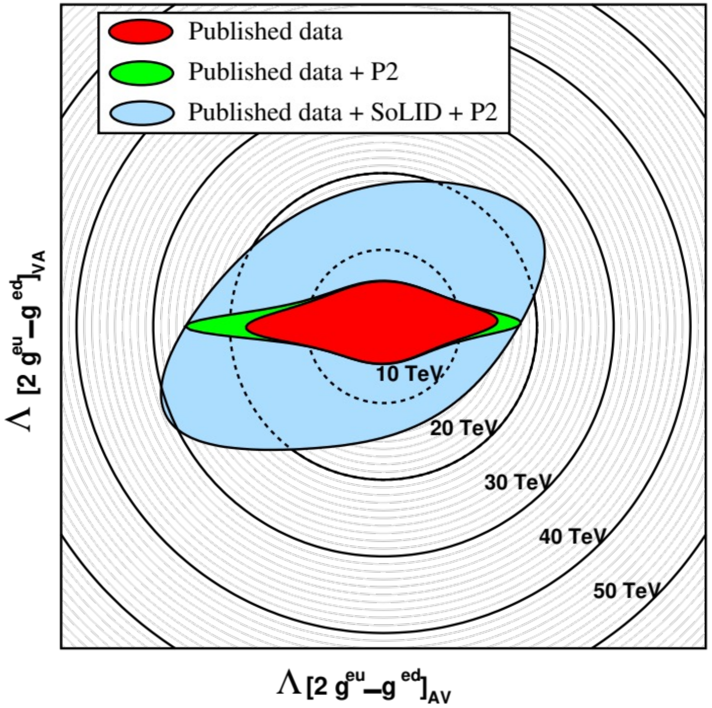
	x	Y	Q^2
New Physics	none	yes	small
CSV	yes	small	small
Higher Twist	large?	no	large

SoLID PVDIS Impact

$$\mathcal{L}_{\rm NC}^{eq} = \frac{1}{2v^2}\left(\bar{e}\gamma^\mu\gamma^5 e \sum_{q=u,d} g_{AV}^{eq}\bar{q}\gamma_\mu q + \bar{e}\gamma^\mu e \sum_{q=u,d} g_{VA}^{eq}\bar{q}\gamma_\mu\gamma^5 q\right)$$

$$A_{RL,d}^{\rm DIS} \approx \frac{3}{20\pi\alpha}\frac{Q^2}{v^2}\left[(2g_{AV}^{eu} - g_{AV}^{ed}) + (2g_{VA}^{eu} - g_{VA}^{ed})\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$





$$\frac{G_F}{\sqrt{2}}g_{ij} \to \frac{G_F}{\sqrt{2}}g_{ij} + \eta_{ij}^q\frac{4\pi}{(\Lambda_{ij}^q)^2}$$

BSM physics probed: leptophobic Z', dark Z, strong PV (https://arxiv.org/abs/2306.04704)

Slide: P. Souder, PAC50

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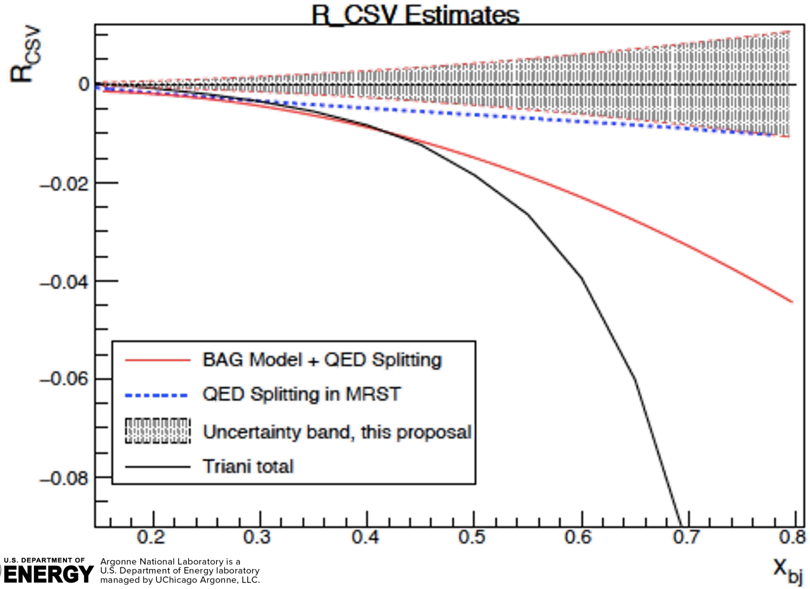
Hadronic Physics: Charge Symmetry Violation

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

⇓

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



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

Slide Credit: P Souder, JLab
Director's Review, Feb 2021

Standard Model Effective Field Theory (SMEFT)

- BSM Physics has large phase space
- PVDIS deuteron measurement access effective electron-quark couplings

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

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

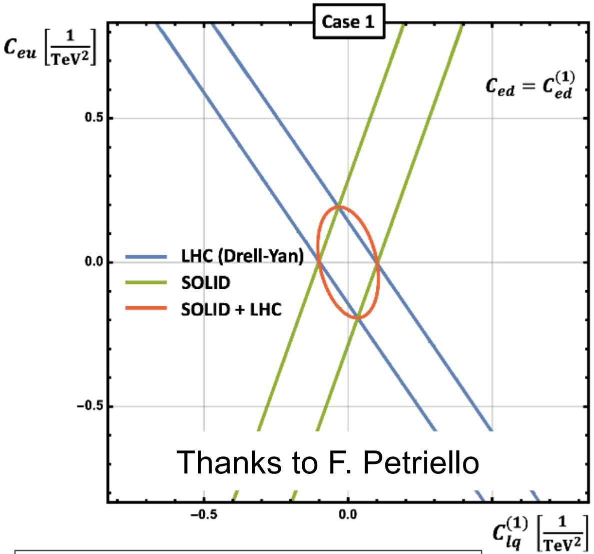
$$e_{L/R} = \frac{1}{2}(1 \mp \gamma^5)\psi_e$$

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

Goal: Measure each C_d^{ij} as precisely as possible
(Nobody really knows where the new physics is.)

SMEFT identifies
all possible BSM physics

84 d=6; 993 d=8 independent couplings



Thanks to F. Petriello

See Euler and Su, Prog. Part. Nucl. Phys. 71 (2013) 119–149

Slide Credit: P Souder, JLab Director's Review, Feb 2021

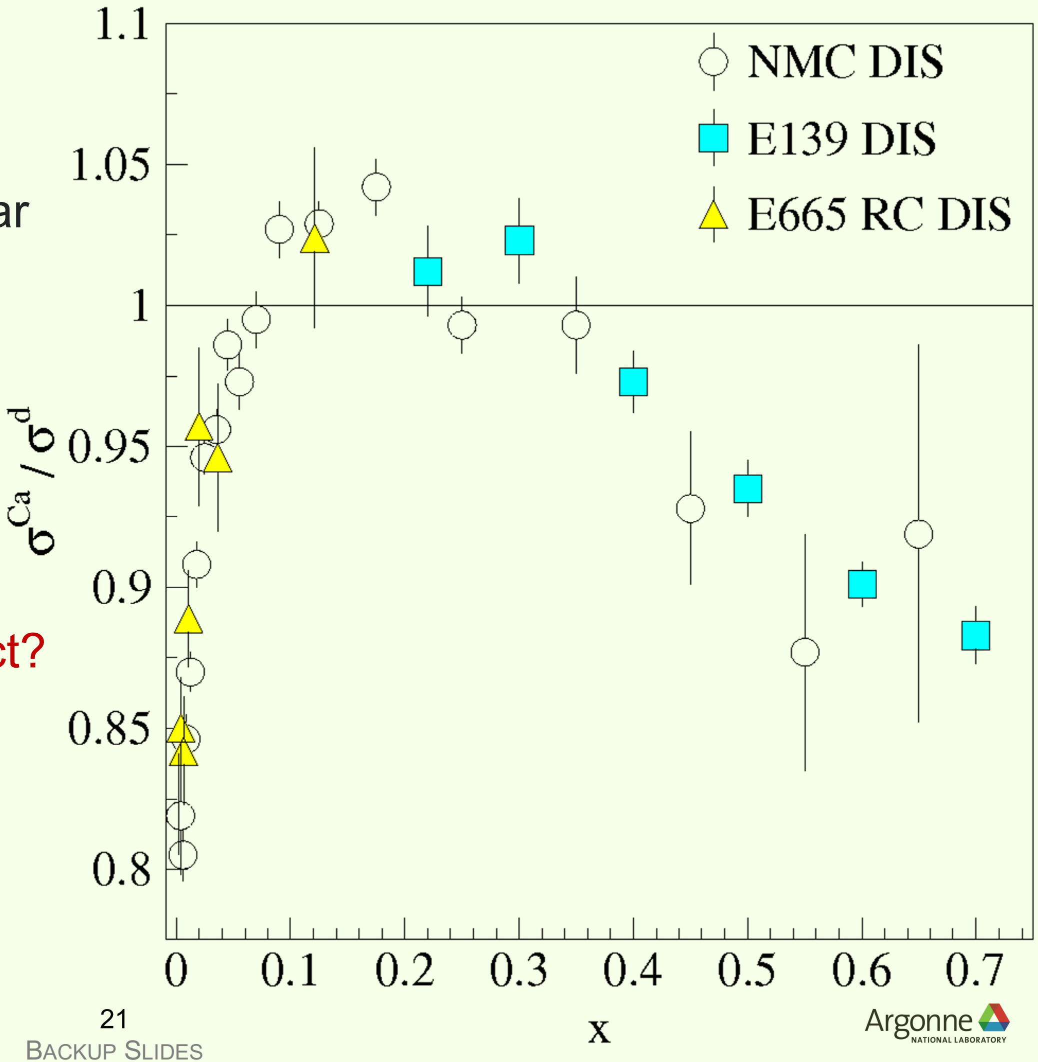
Probing the EMC Effect

What we know:

- Parton distributions in nuclei appear different than those in nucleons

What we don't know:

- Is the sea quark effect absent?
  - see Drell-Yan from SeaQuest
- Is there a **flavor dependent** effect?
  - c.f. Cloët PRL 102 252301 (2009)
- **Why** does the effect exist at all?



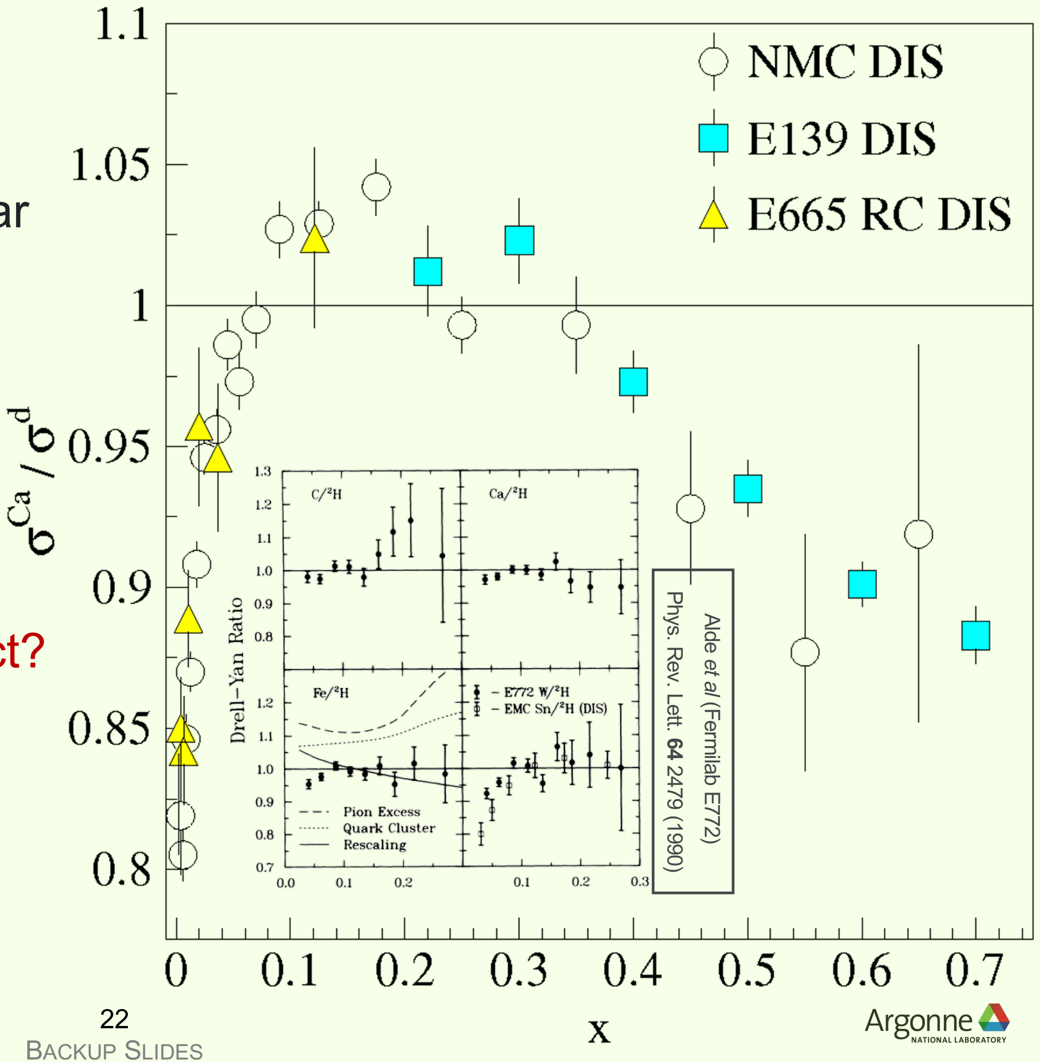
PROBING THE EMC EFFECT

What we know:

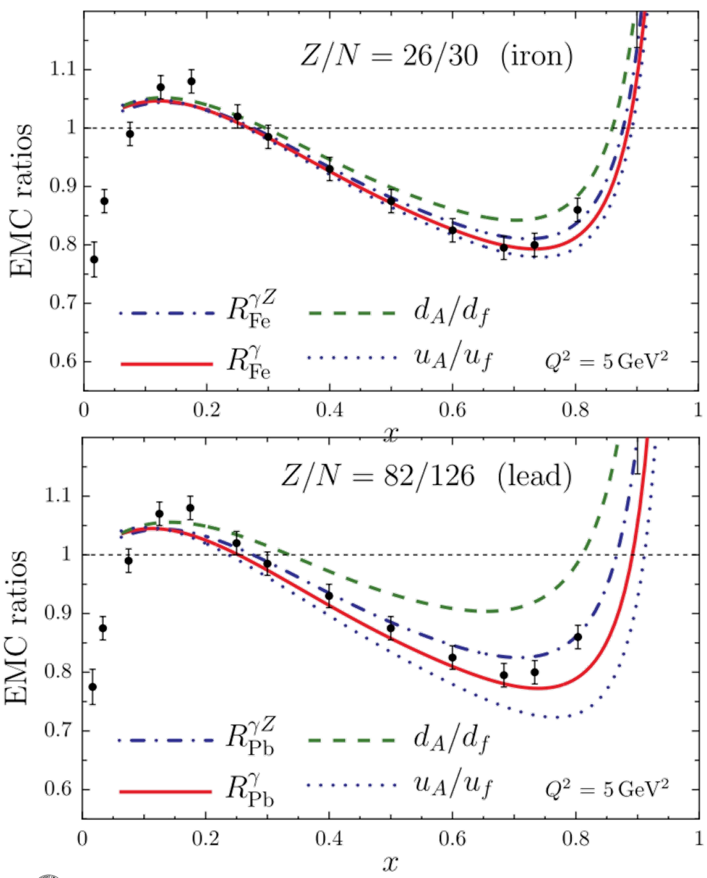
- Parton distributions in nuclei appear different than those in nucleons
  - except, possibly for sea quarks

What we don't know:

- Is the sea quark effect absent?
  - see Drell-Yan from SeaQuest
- Is there a **flavor dependent** effect?
  - c.f. Cloët PRL 102 252301 (2009)
- **Why** does the effect exist at all?



Flavor Dependent EMC
a la Cloët



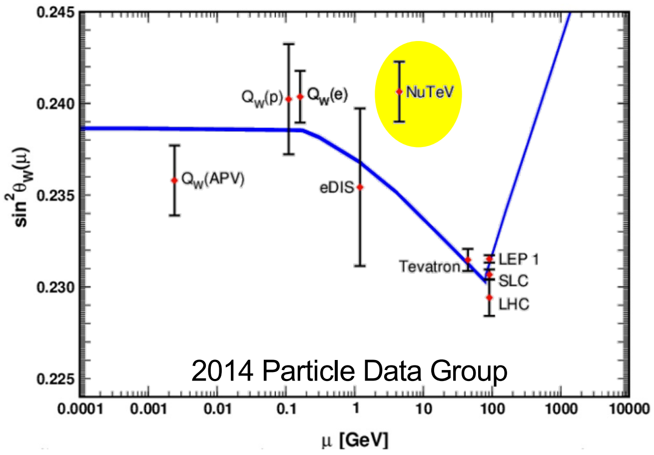
Traditional models and explanations of the EMC effect assume that the effect is the same for all flavors of quarks

$$\frac{u_A(x)}{u_f(x)} \equiv \frac{d_A(x)}{d_f(x)}$$

This symmetry is not demanded by any underlying physics!

NuTeV:

- SM test based on neutrino scattering
- Tour de force experiment in many aspects except
- Weakly interacting ν beam required a dense target—Fe
- Flavor dependent nuclear effects can explain much of the NuTeV anomaly



2014 Particle Data Group

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PVEMC

$$A_{PV} \approx -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[\boldsymbol{a_1}(x) + \frac{1-(1-y)^2}{1+(1-y)^2}\boldsymbol{a_3}(x)\right]$$

$$\boldsymbol{a_1}(x) = g_A^e \frac{F_1^{\gamma Z}}{F_{1A}^{\gamma}} = 2\frac{\sum C_{1i} e_i [q_i(x) + \bar{q}_i(x)]}{\sum e_i^2 [q_i(x) + \bar{q}_i(x)]}$$

$$\boldsymbol{a_3}(x) = g_A^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}} = 2\frac{\sum C_{1i} e_i [q_i(x) - \bar{q}_i(x)]}{\sum e_i^2 [q_i(x) + \bar{q}_i(x)]}$$

Approximate $\boldsymbol{a_1}(x)$ around symmetric nucleus

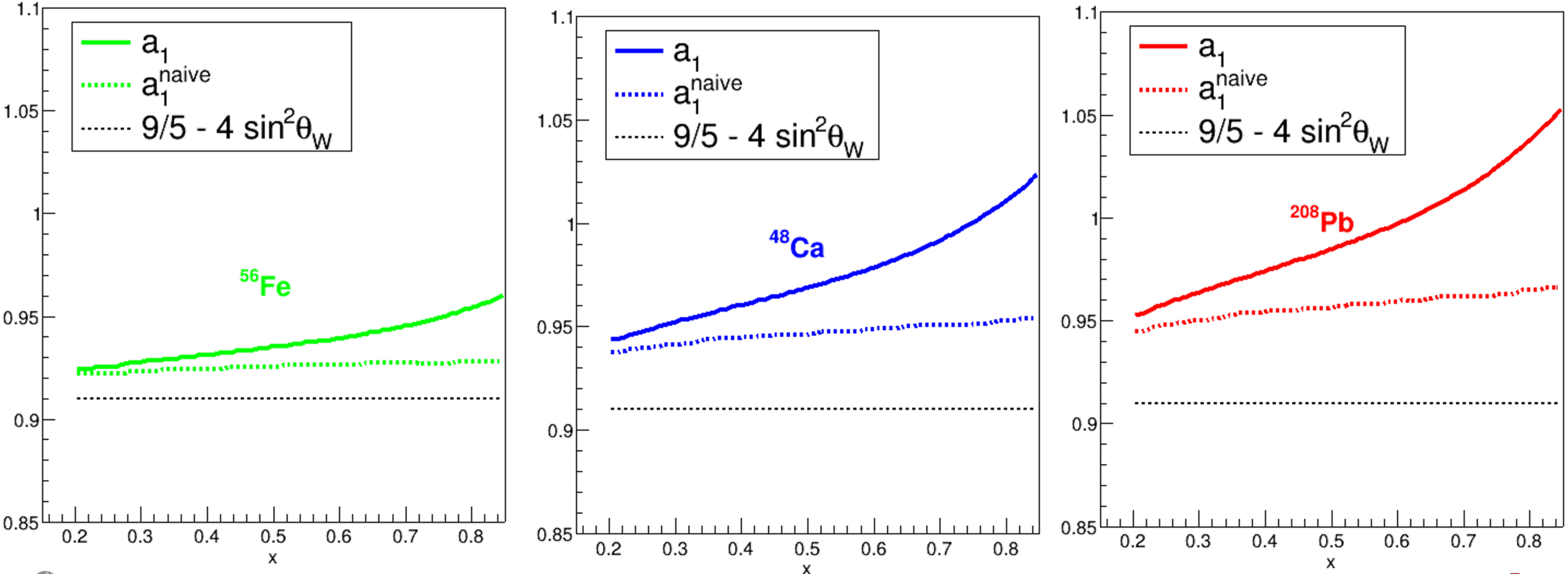
$$\boldsymbol{a_1}(x) \simeq \frac{9}{5} - 4\sin^2\theta_W - \left(\frac{12}{25}\right)\frac{\boldsymbol{u_A^+} - \boldsymbol{d_A^+}}{\boldsymbol{u_A^+} + \boldsymbol{d_A^+}}$$

$$q^{\pm}(x) = q(x) \pm \bar{q}(x)$$

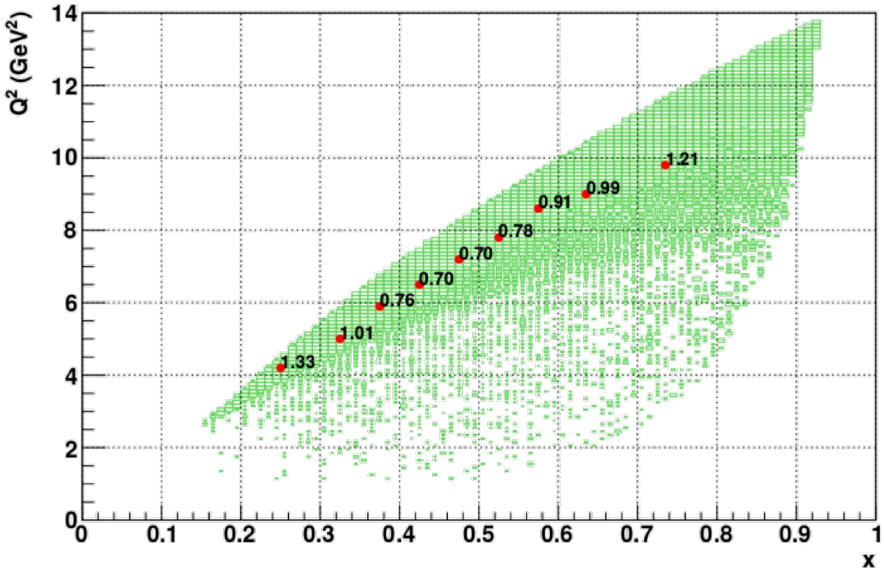
Measures flavor differences!

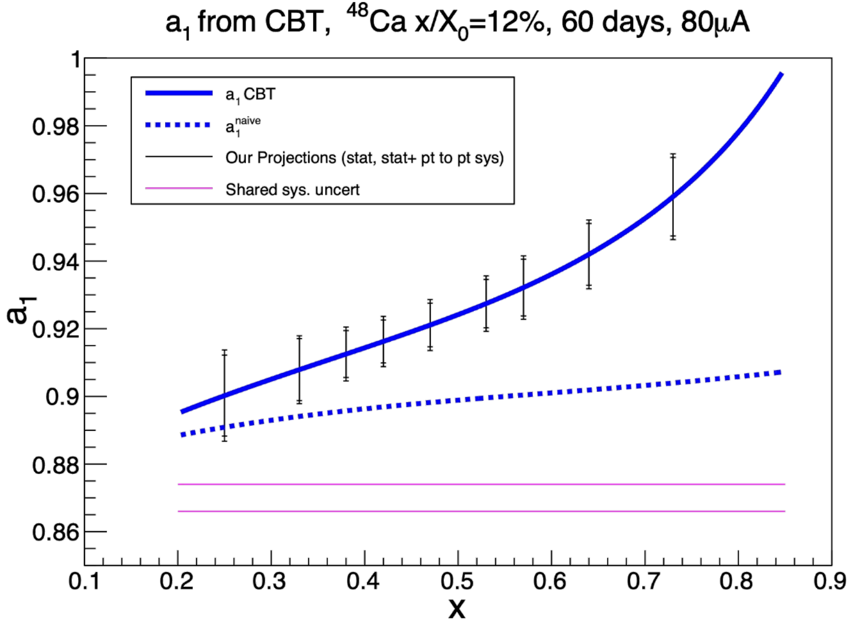
$a_1(x)$ for Nuclei

$$a_1(x) \simeq \frac{9}{5} - 4\ \sin^2\theta_W - \left(\frac{12}{25}\right)\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$



Expected Results





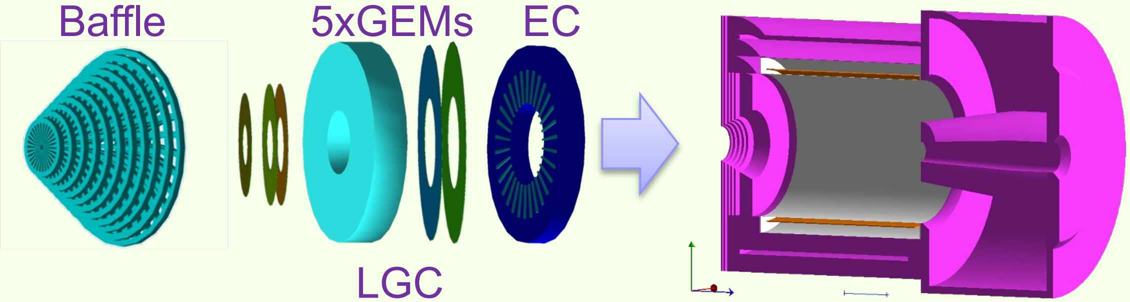
Recap

- Parity violation in DIS enables electroweak and QCD exploration

$$A_{\mathrm{PV}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{\mathrm{weak}} - \mathcal{M}^r_{\mathrm{weak}}}{\mathcal{M}_{\mathrm{EM}}}$$

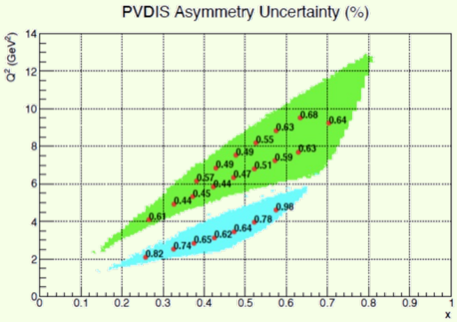
Half full or half empty

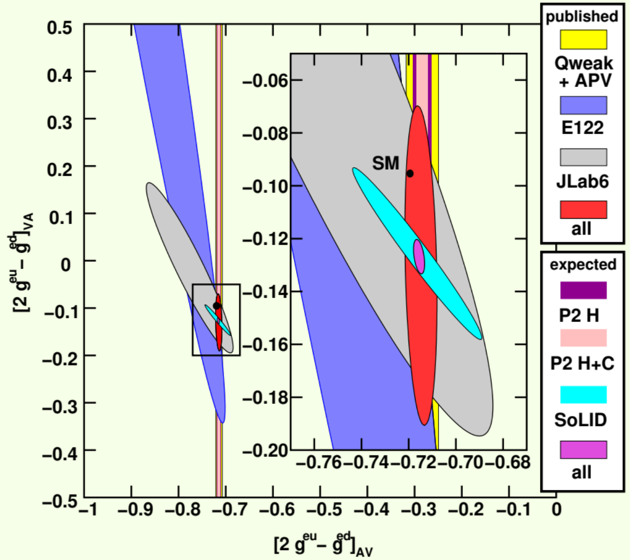
- SoLID mission (one of several) is to used PVDIS for electroweak and QCD study



RECAP

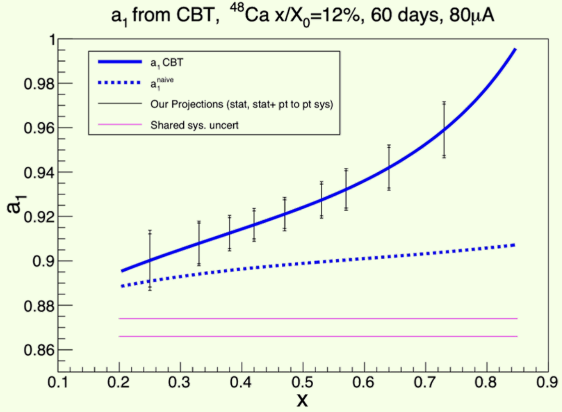
- SoLID PVDIS has significant reach to explore the SM





- SoLID flavor-dependence in the EMC Effect

$$\boldsymbol{a_1}(x) \simeq \frac{9}{5} - 4\ \sin^2\theta_W\ - \frac{\boldsymbol{12u_A^+ - d_A^+}}{\boldsymbol{25u_A^+ + d_A^+}}$$



$$A_{PV}^{eDIS} = \frac{\sigma^e - \sigma^l}{\sigma^e + \sigma^l}$$

- $$= 2\,\frac{sy}{M_Z^2}\,\frac{g_A^e \sum Q_A^q g_V^q [q(x) + \bar{q}(x)]\left[1+(1-y)^2\right] + g_V^e \sum Q_A^q g_A^q [q(x) - \bar{q}(x)]\left[1-(1-y)^2\right]}{Q_A^e \sum \left(2Q_A^q\right)^2 [q(x) + \bar{q}(x)][1+(1-y)^2]}$$

$$\approx \frac{3}{20\pi\alpha(Q)}\,\frac{Q\text{^}2}{\nu}\left[\left(2g_{AV}^{eu} - g_{AV}^{ed}\right) + \left(2g_{VA}^{eu} - g_{VA}^{ed}\right)\left(\frac{1-(1-y)^2}{1+(1-y)^2}\right)\right]$$

UNIQUE HIGHER TWIST CONTRIBUTION

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)

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

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

Isospin decomposition before using PDF's

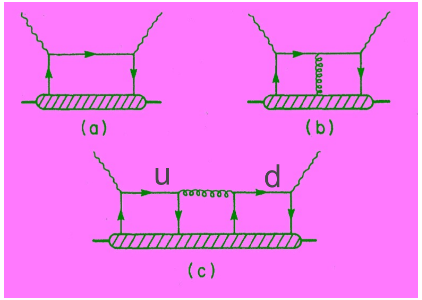
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y) b(x)\right]$$

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

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

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



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

σ_L contributions cancel

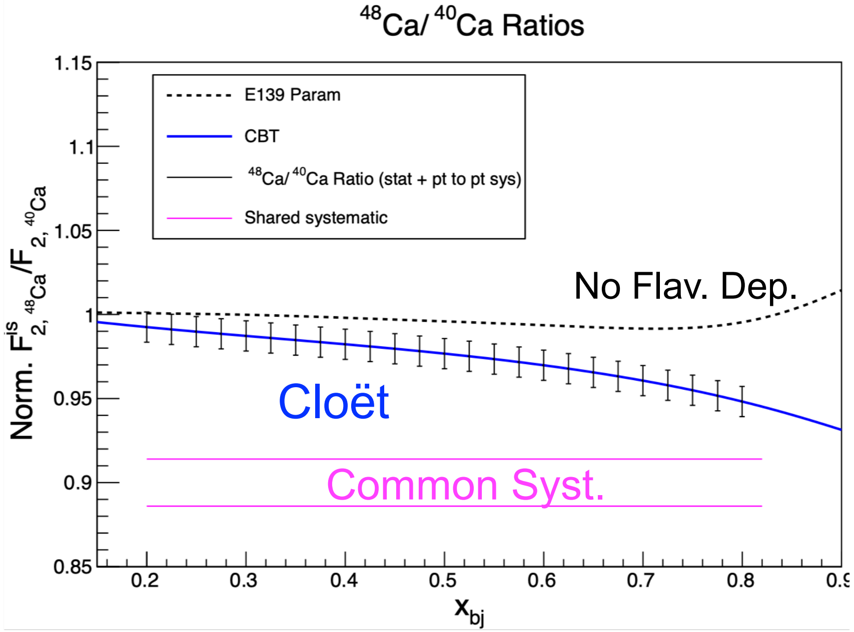
Slide Credit: P Souder, JLab Director's Review, Feb 2021

Why use Parity Violation?

- $^{48}Ca/^{40}Ca$ ratio (E12-10-008)
  - will be less than fully conclusive

- $^{3}H/^{3}He$ (MARARHON)
  - more sensitive to neutron structure function than flavor dependence

- π^+/π^- from $^{3}H/^{3}He$ (12-21-004 Hall B)
  - Conditional approval
  - PAC "The physics programme is very rich, but the extraction of the underlying physics observables is very challenging"



Possible Lepto-Phobic Z'; Example at lower energy

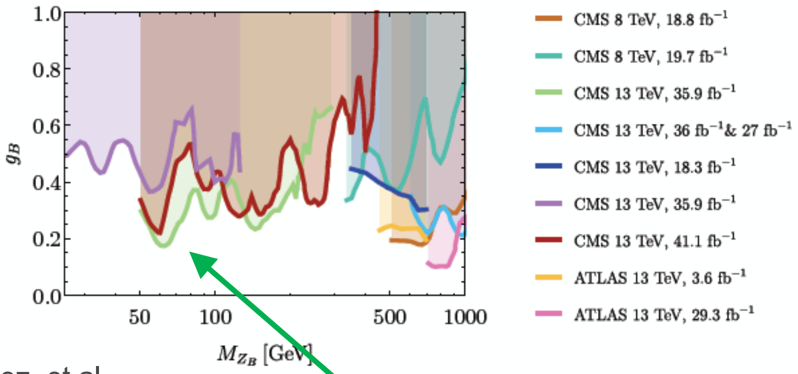
Motivation for introducing new particle:

C2

Baryon number is a global symmetry in the SM (bad).
Theories of local baryon number symmetry are attractive.
They predict a lepto-phobic boson.
They also predict a dark matter candidate.

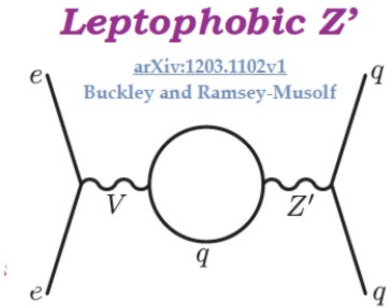
$$A \sim \frac{(gB)2}{(M_{Z'})^2}$$

Perez, Phys. Rept. 597, (2015) 1-30



Perez, et al.,
JHEP 07 (2020) 087

Limits depend on branching ratios.



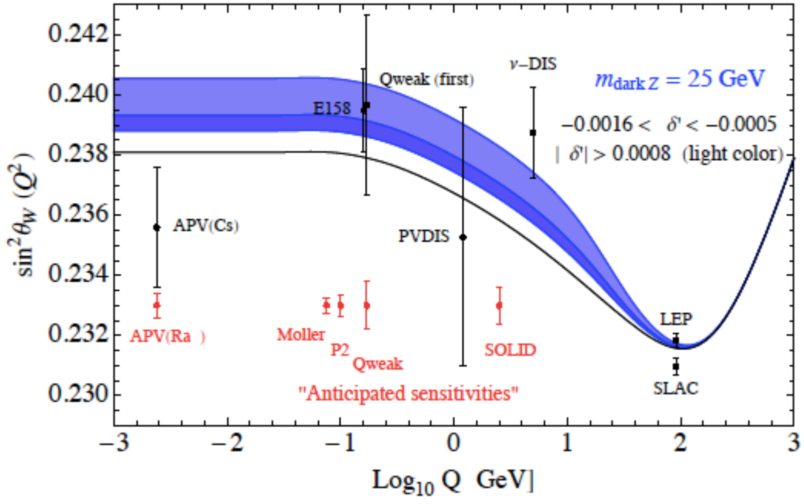
Modifies mainly C_2's in PVES

Plot shows that the LHC is interested in Leptophobics

Dark Boson Z_d and $\sin^2\theta_W$

C2

- *Davoudiasl, et al. Phys.Rev.D* 92 (2015) 5, 055005



PVES is the only way to see Z_d if decay is dominated by invisible particles

Method:

1. Assume Standard Model
2. Treat C_i's as function of $\sin^2\theta_W$
3. Fit to one parameter