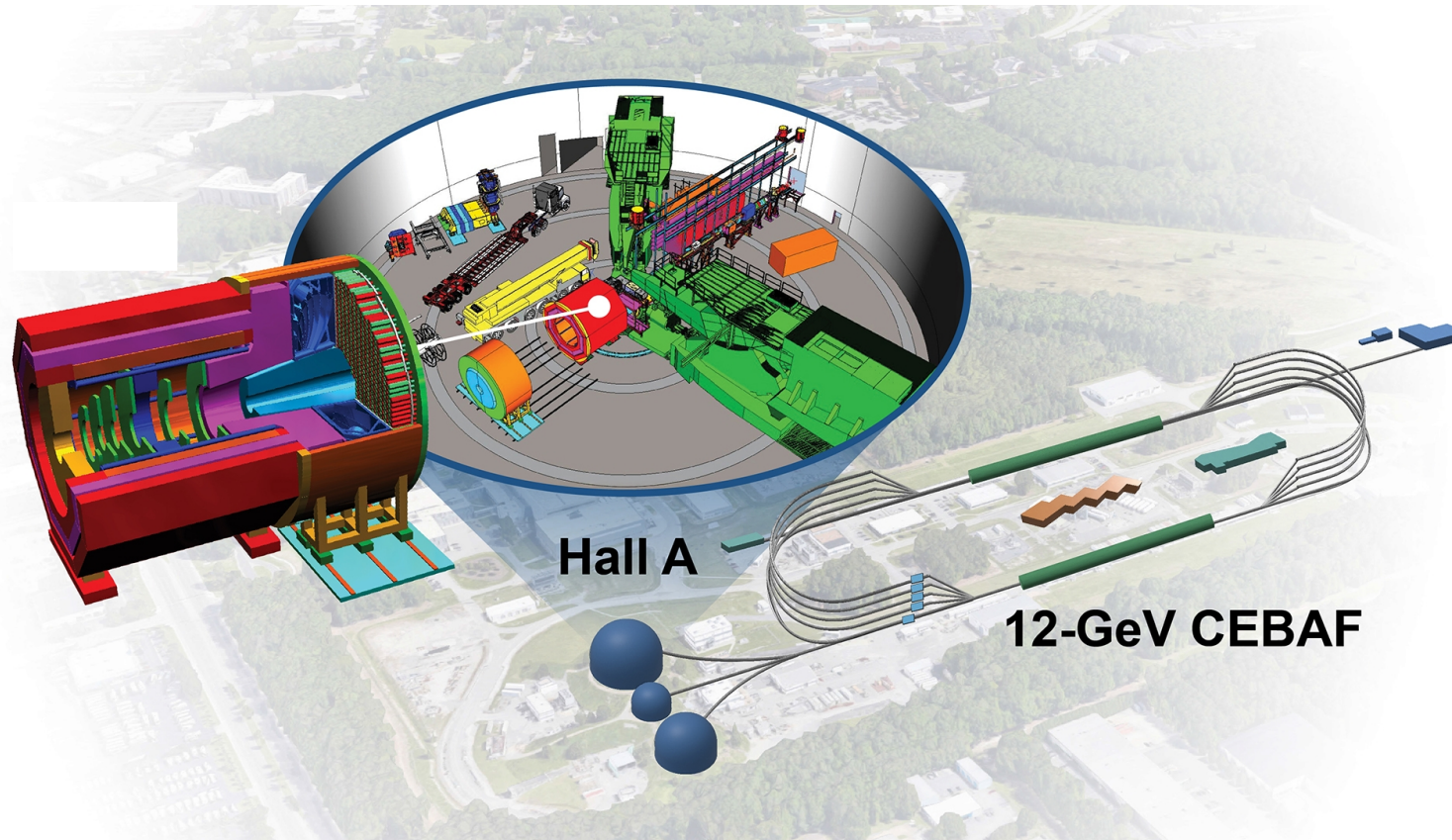


Test of Standard Model with PVDIS at JLab



High Luminosity
Workshop

October 5-9, 2026

Xiaochao Zheng

University of Virginia

<https://arxiv.org/abs/2209.13357>
(J.Phys.G 50 (2023) 11, 110501)

The Next-Generation Spectrometer

To **maximize** the science return of the 12-GeV CEBAF upgrade. We need to measure small cross sections and asymmetries with high or meaningful precision by combining:

High Luminosity

$10^{37-39} / (\text{cm}^2 \cdot \text{s})$
[>100x CLAS12] [>1000x EIC]



Large Acceptance

Full azimuthal ϕ coverage

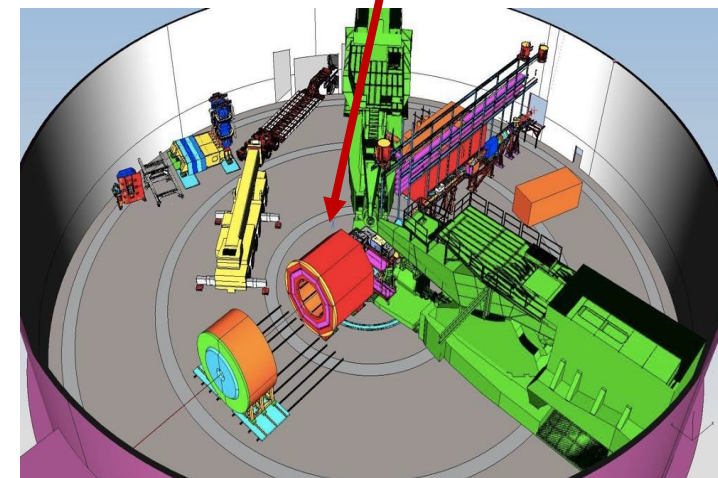
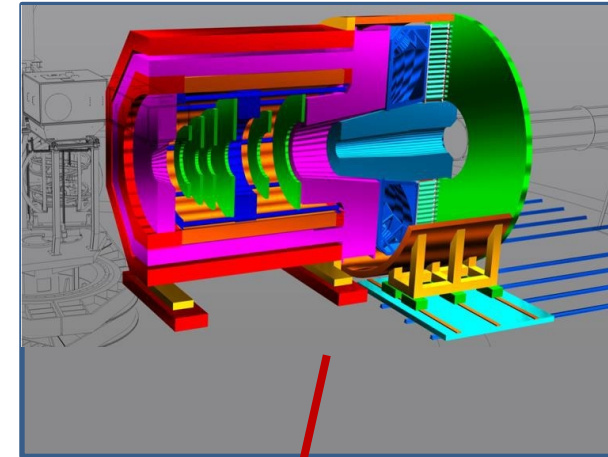


Three pillars of the Science program:

- Imaging the proton **spin** from 1D (PDF) to 3D or more in SIDIS
- J/Psi threshold studies to probe the proton **mass** and gluonic field
- High precision PVDIS and test of the **electroweak** Standard Model

We will measure processes never measured before:

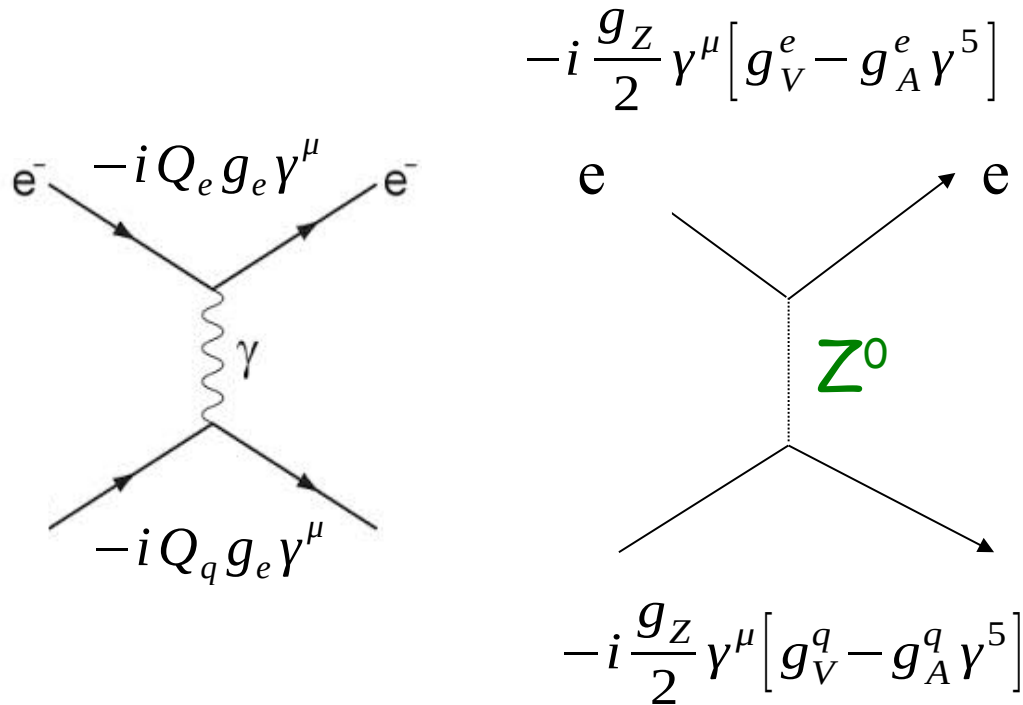
- New observables: Beam-normal single-spin asymmetry (SSA) in DIS
- Deep exclusive processes – DDVCS, etc.



Parity Violation in Deep Inelastic Scattering

- We detect only one particle – the e'
- We measure only one observable – the R-L asymmetry (A_{PV})
- We extract only one number – $C2q$ (or $\sin^2\theta_W$, pick your favorite)
- We even use only one kinematic variable – Q^2
- Possible number of BSM models we can constrain – Infinite

Parity Violation in Deep Inelastic Scattering

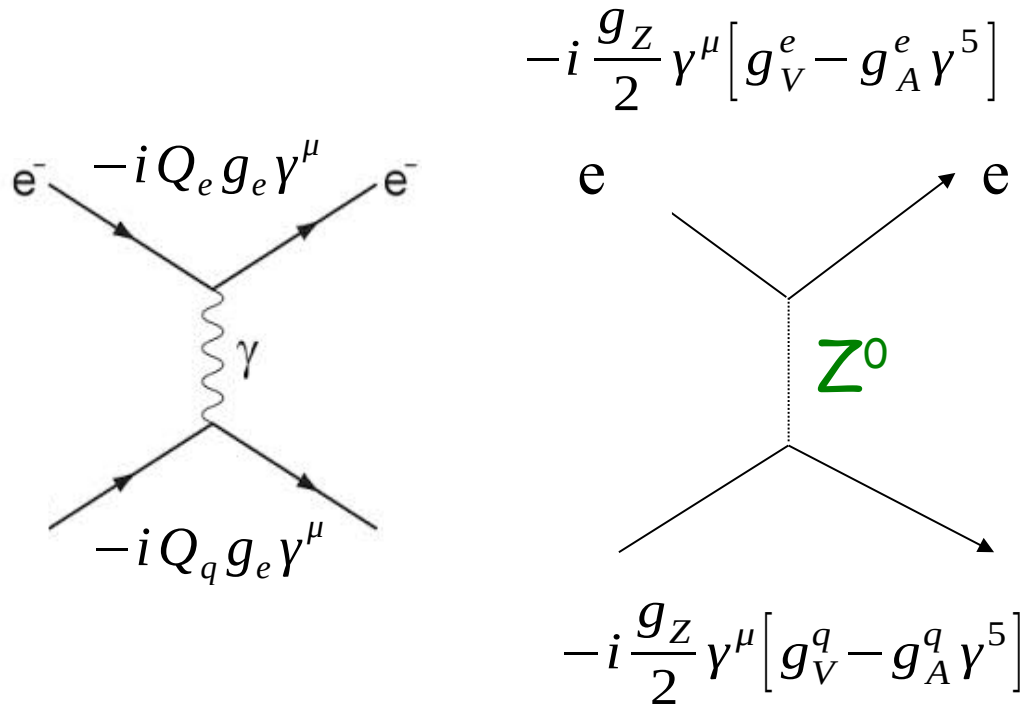


At $Q^2 \ll M_Z^2$

$$A_{PV} \approx \frac{Q^2}{M_Z^2} \approx 90 \text{ ppm/GeV}^2 \times Q^2$$

fermion	Q_f	c_A^f	c_V^f
ν_e, ν_μ, ν_τ	0	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2 \sin^2 \theta_W \approx -0.03$
u, c, t	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3} \sin^2 \theta_W \approx 0.19$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W \approx -0.34$

Parity Violation in Deep Inelastic Scattering

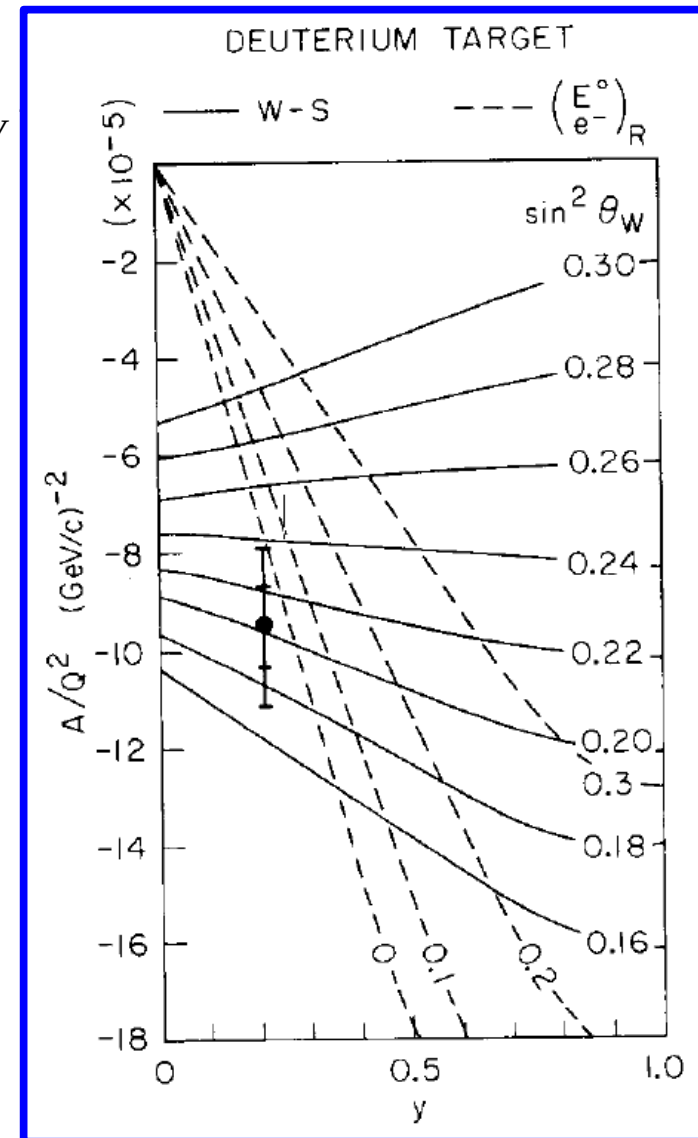


At $Q^2 \ll M_Z^2$

A_{PV}

fermion	Q_f	c_A^f	c_V^f
ν_e, ν_μ, ν_τ	0	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2 \sin^2 \theta_W \approx -0.03$
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d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W \approx -0.34$

Prescott et al, Phys.
Lett. 77B, 347 (1978)



PVDIS on the deuteron

Full expression:

$$A_{RL}^{e^-} = \frac{|P_b| \eta_{\gamma Z} \left[g_A^e 2y F_1^{\gamma Z} + g_A^e F_2^{\gamma Z} \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2 xy}{Q^2} \right) + g_V^e (2-y) F_3^{\gamma Z} \right]}{2y F_1^{\gamma} + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2 xy}{Q^2} \right) F_2^{\gamma} - \eta_{\gamma Z} \left[g_V^e 2y F_1^{\gamma Z} + g_V^e \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2 xy}{Q^2} \right) F_2^{\gamma Z} + g_A^e (2-y) F_3^{\gamma Z} \right]}$$

To a good approximation:

$$A_{RL,d}^{e^-, \text{PVDIS}} \approx |\lambda| \frac{3G_F Q^2}{10\sqrt{2}\pi\alpha} [(2C_{1u} - C_{1d}) + R_V Y (2C_{2u} - C_{2d})]$$

spin flip

PVDIS on the deuteron

Full expression:

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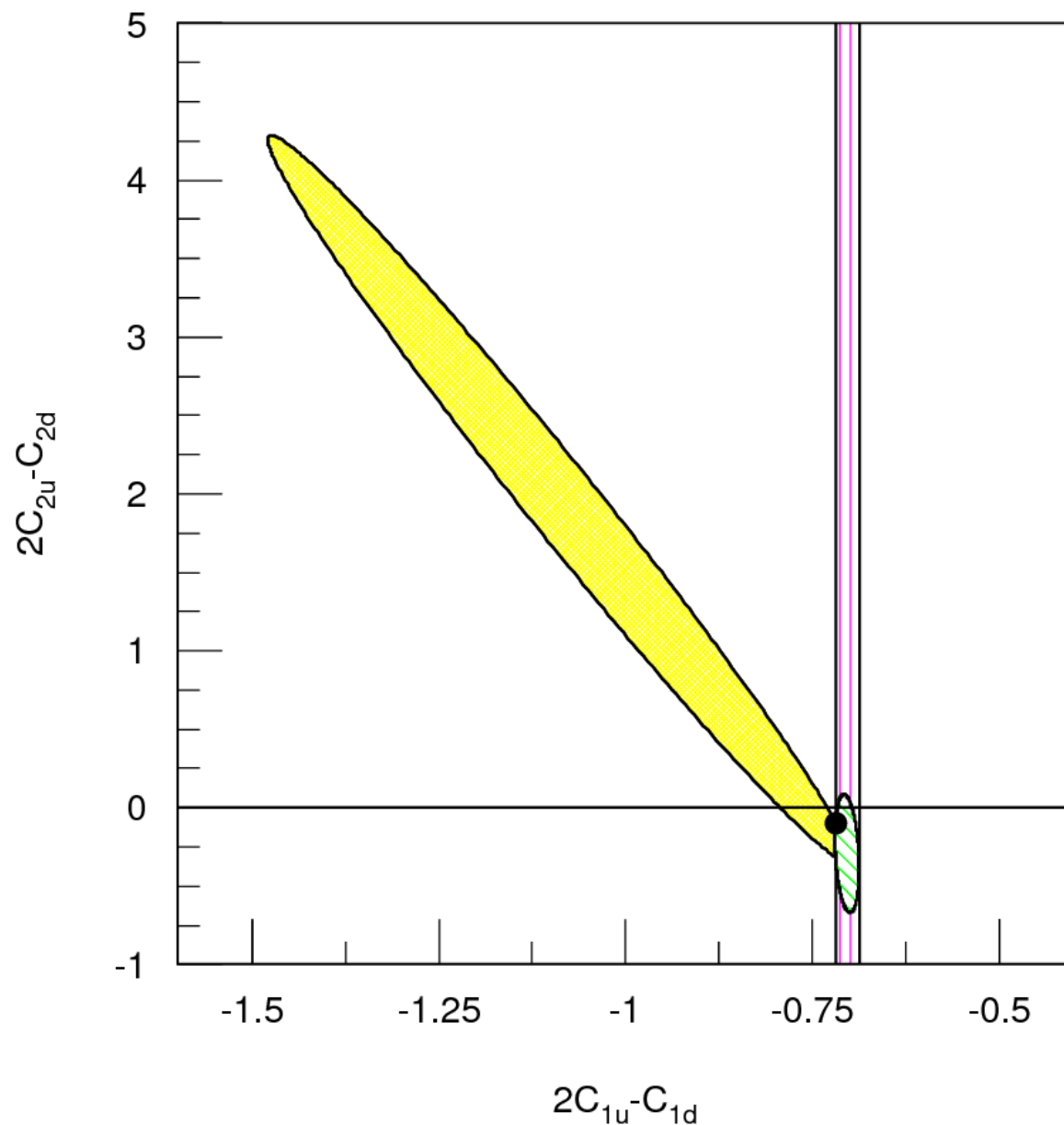
spin flip

Note: elastic PVES or
Atomic PV access C_{1q} .
Example: $Q_W^p \sim 2C_{1u} + C_{1d}$

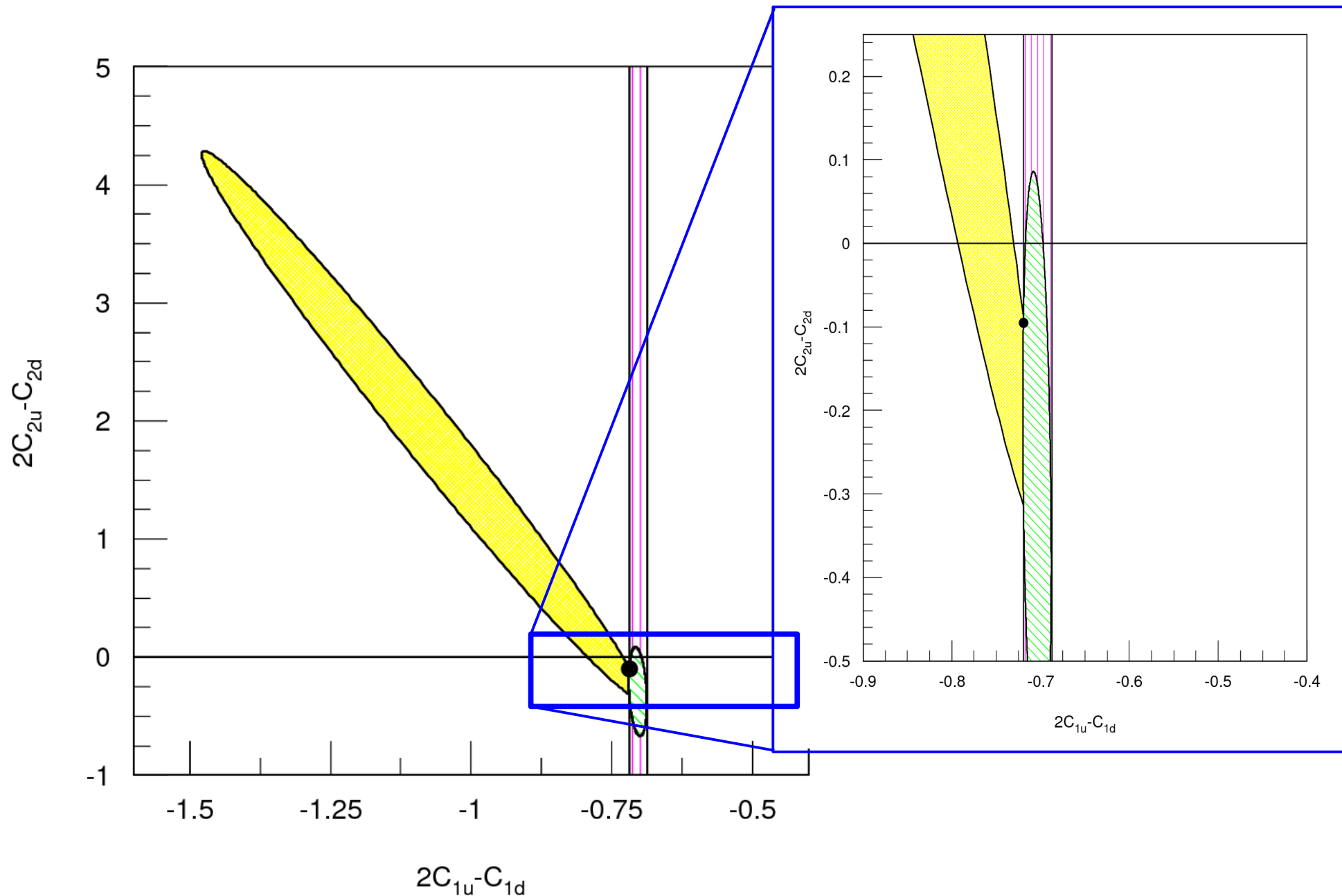
$$g_{AV}^{eu} = C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W; \quad g_{AV}^{ed} = C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W$$

$$g_{VA}^{eu} = C_{2u} = -\frac{1}{2} + 2 \sin^2 \theta_W; \quad g_{VA}^{ed} = C_{2d} = \frac{1}{2} - 2 \sin^2 \theta_W.$$

C1, C2 from E122 and Elastic + APV



C1, C2 from E122 and Elastic + APV



Hall A 6 GeV PVDIS (E05-007/E08-011)

- 6.0 GeV beam, 20 cm LD2, 100uA beam, 30 PAC days
- Two HRSs, DC off, scaler-based DAQ

$$A_{Q^2=1.085, x=0.241}^{phys} = -91.10 \pm 3.11 \pm 2.97 \text{ ppm}$$

compare to

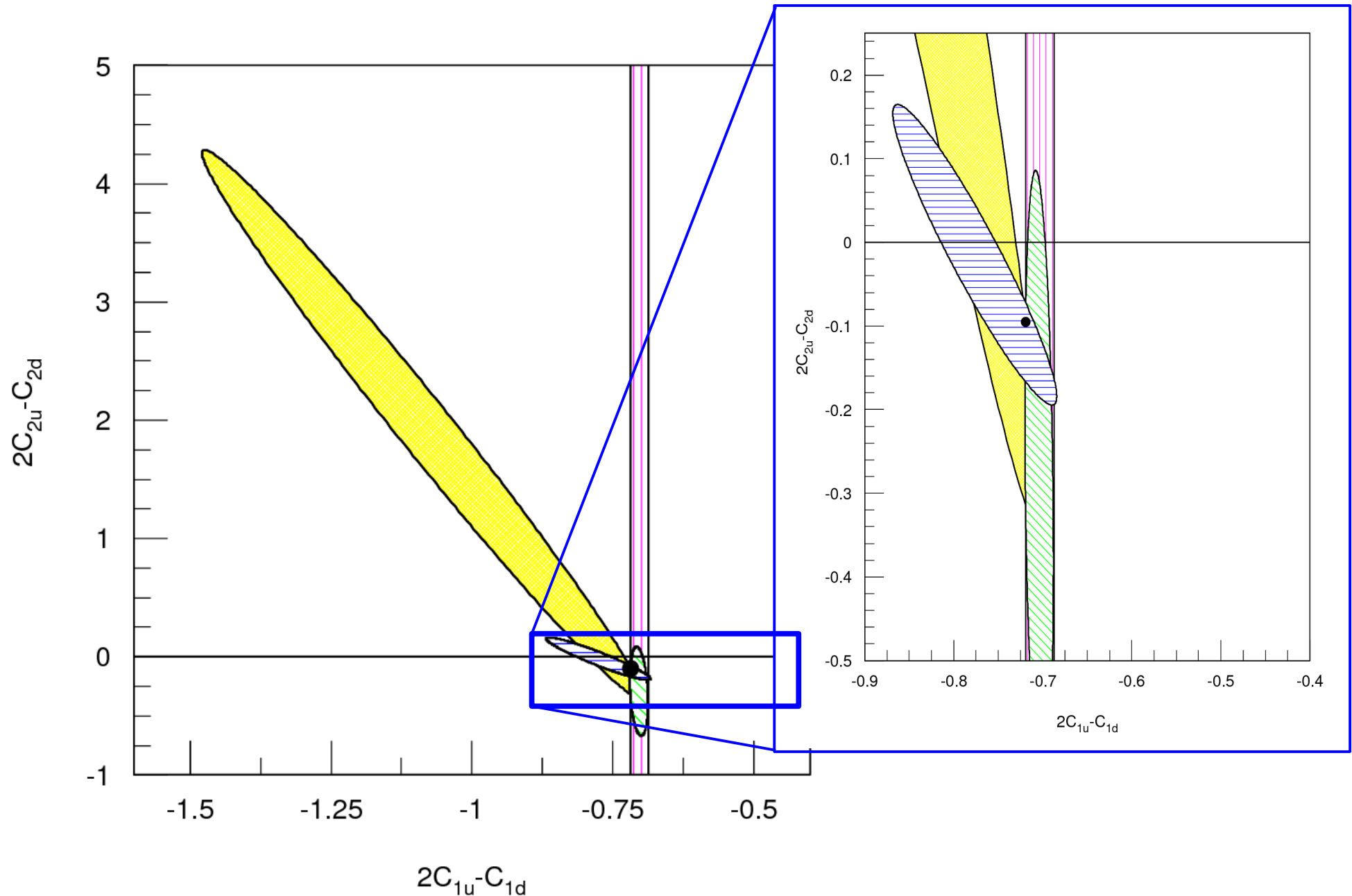
$$A^{SM} = (1.156 \times 10^{-4}) \left[(2 C_{1u} - C_{1d}) + 0.348 (2 C_{2u} - C_{2d}) \right]$$

$$A_{Q^2=1.901, x=0.295}^{phys} = -160.80 \pm 6.39 \pm 3.12 \text{ ppm}$$

compare to

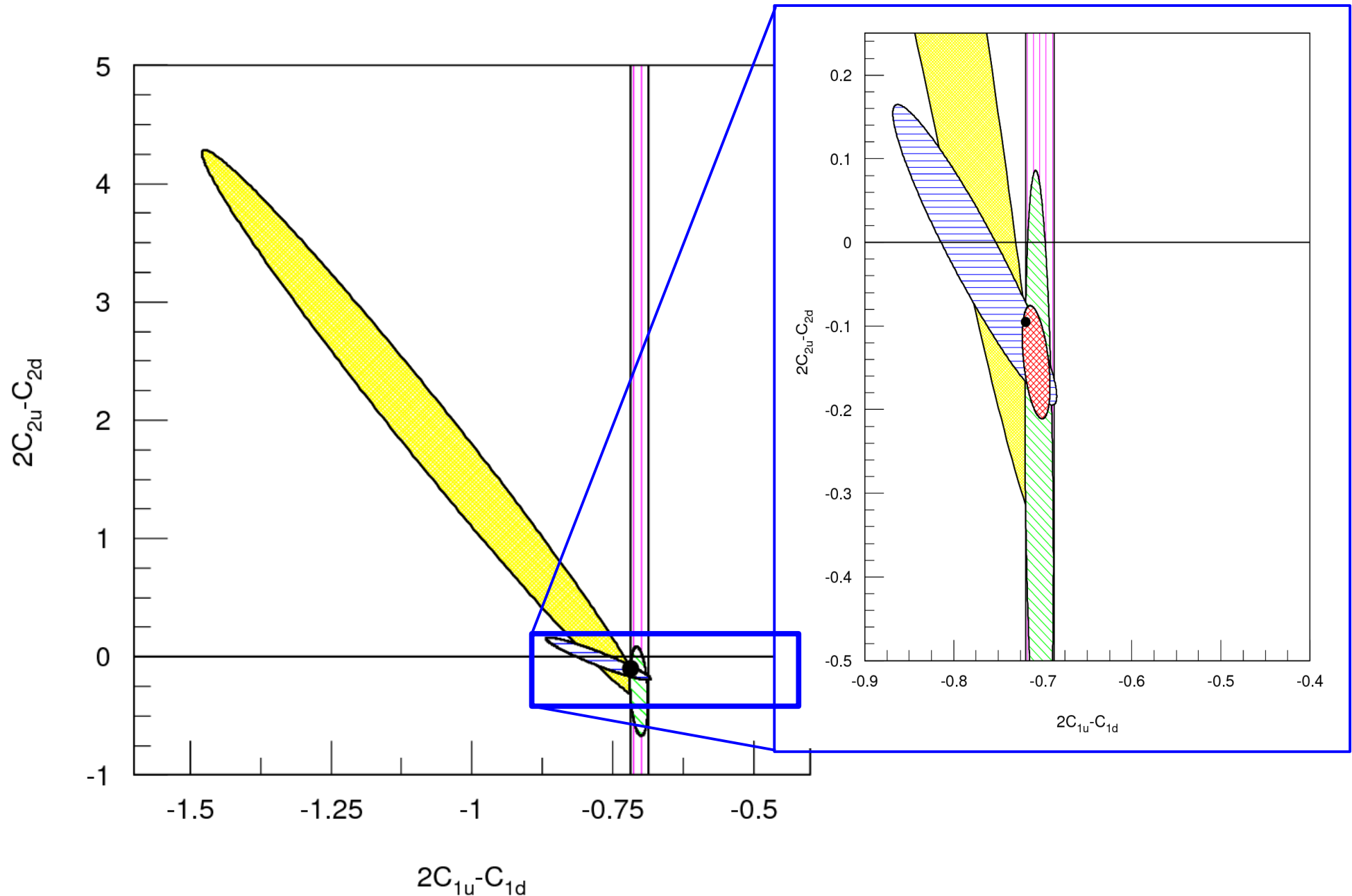
$$A^{SM} = (2.022 \times 10^{-4}) \left[(2 C_{1u} - C_{1d}) + 0.594 (2 C_{2u} - C_{2d}) \right]$$

C1, C2 from Hall A 6 GeV PVDIS



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

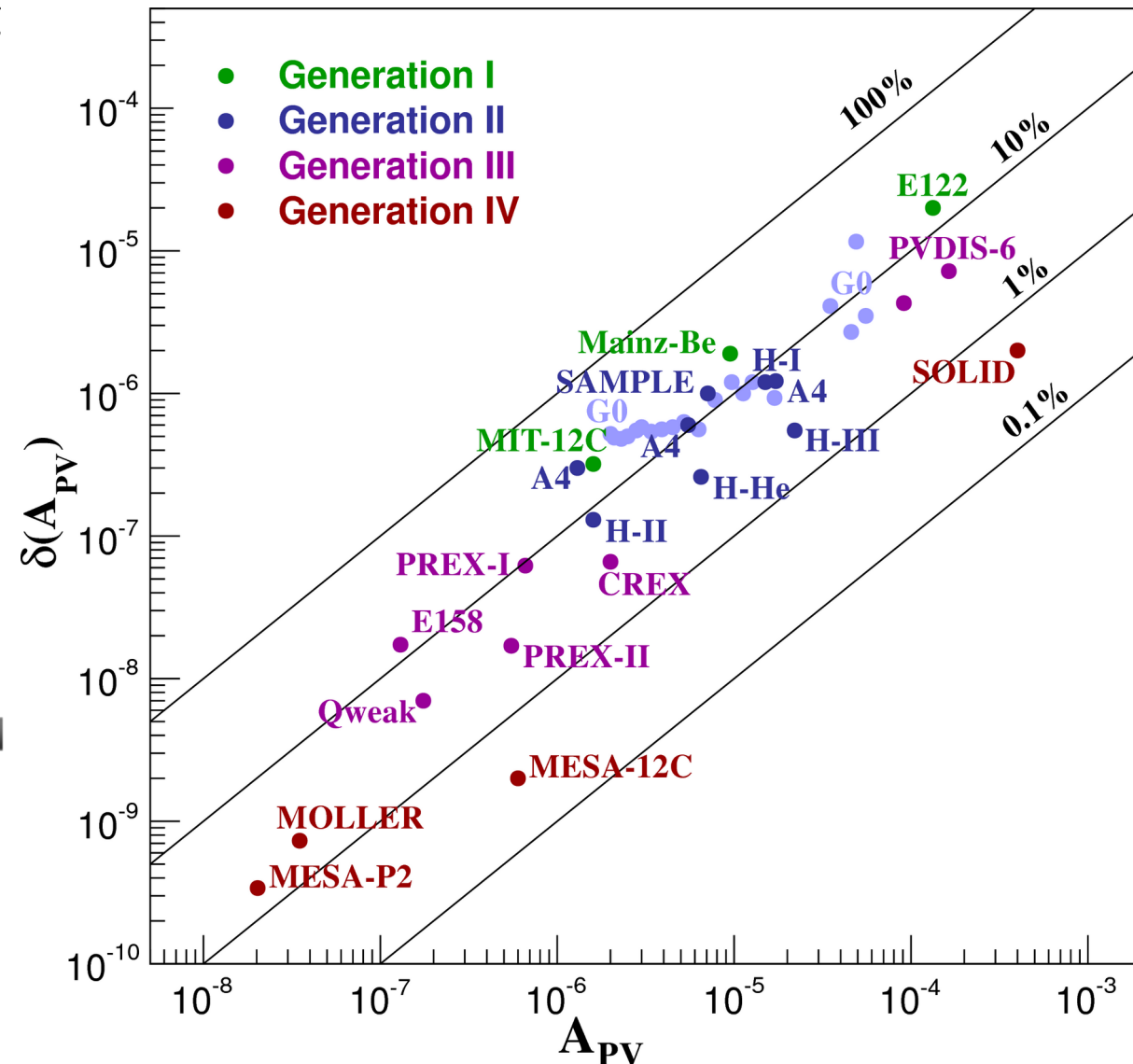
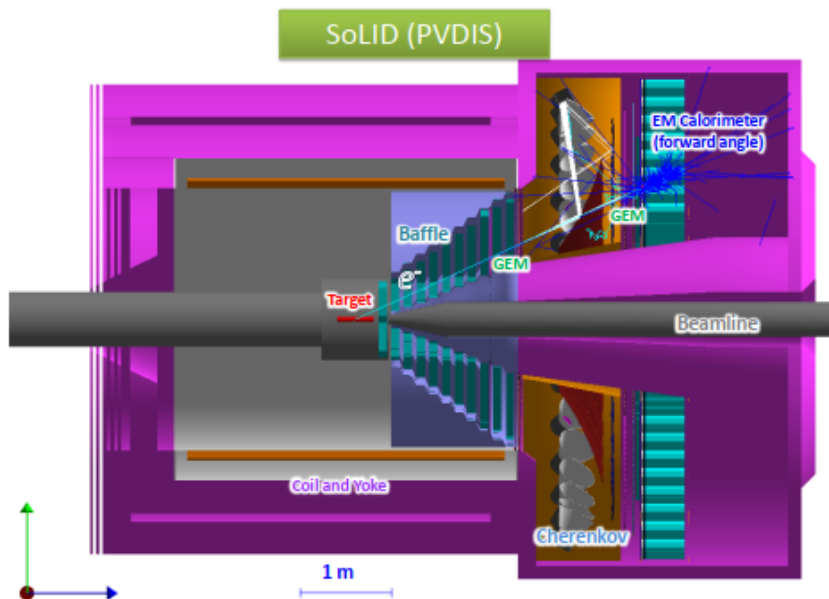
C1, C2 from Hall A 6 GeV PVDIS



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

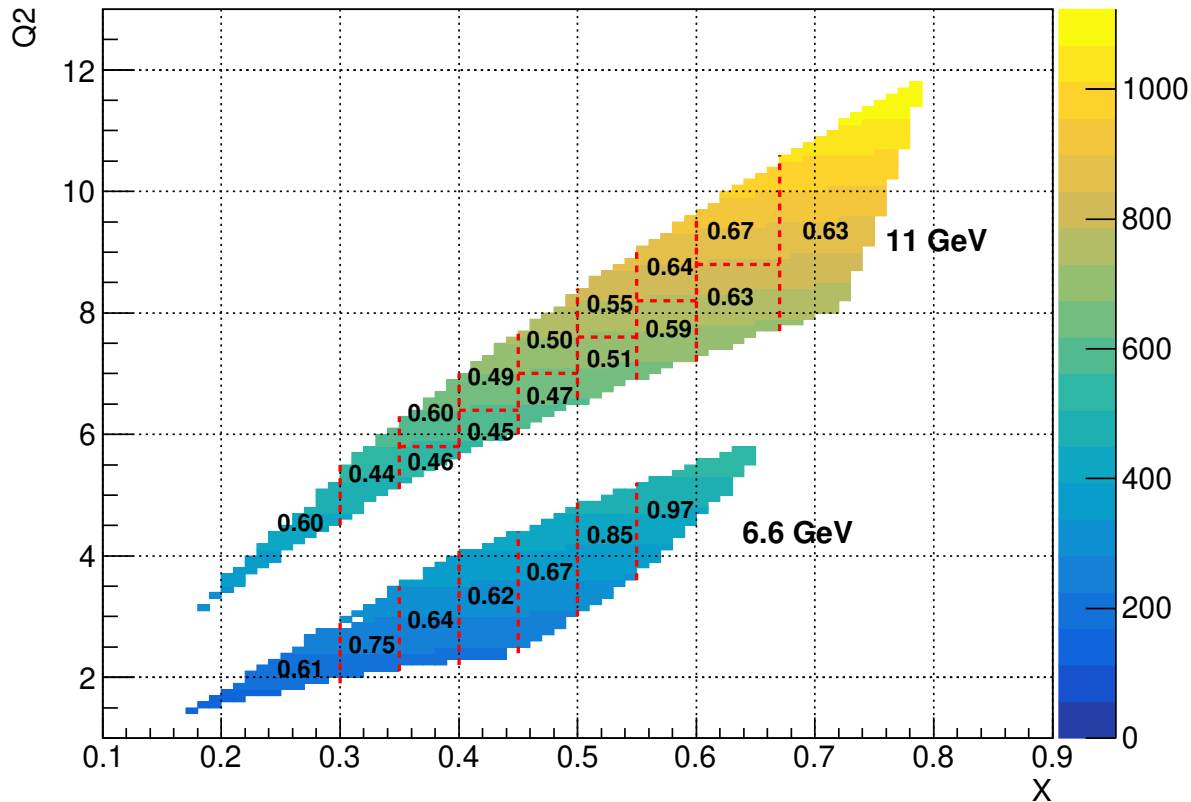
PVDIS with High Luminosity

- 11.0 GeV beam, 40 cm LD2, 50uA beam, 120 PAC days
- additional lower energy running



PVDIS with High Luminosity

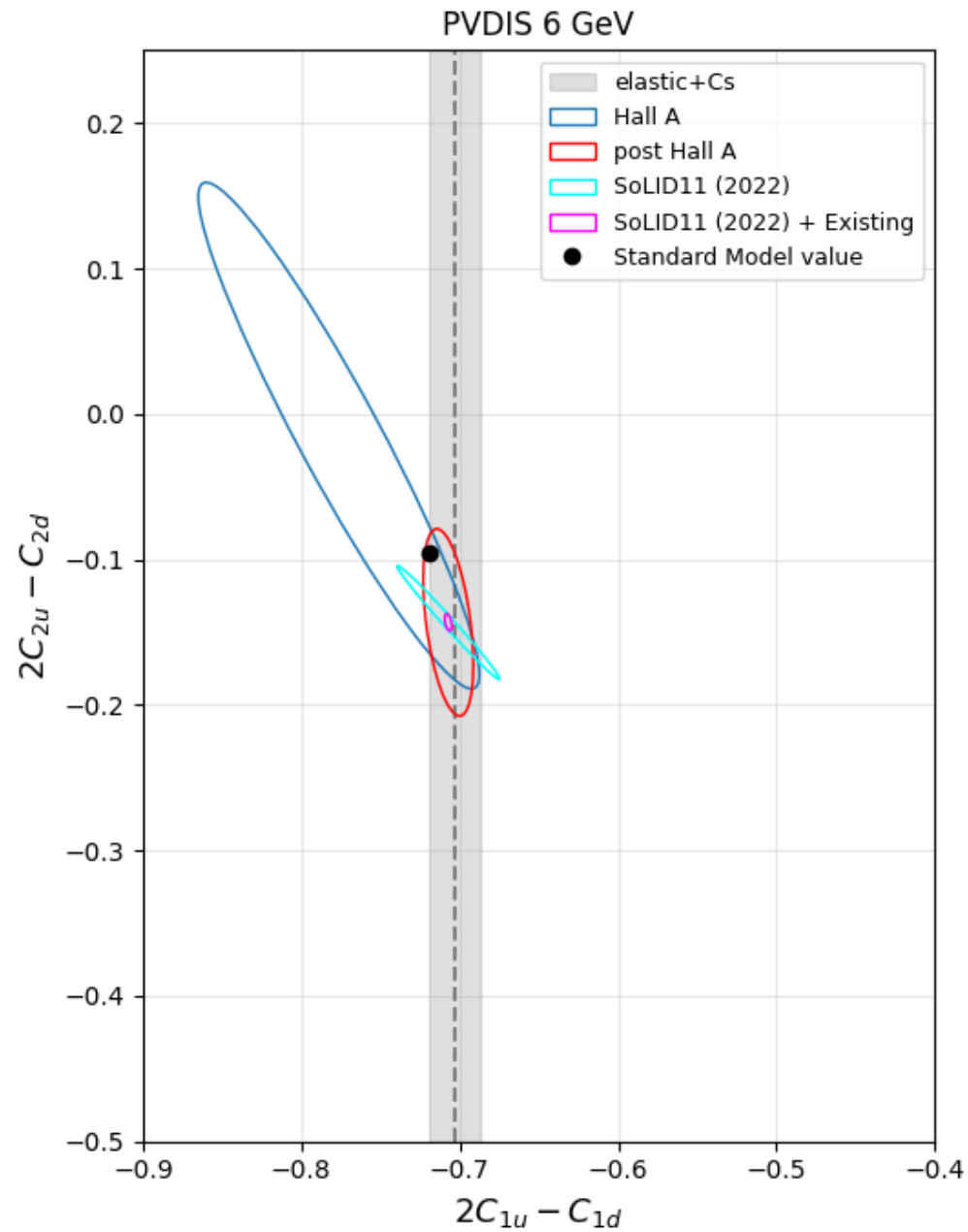
SoLID Apv(ppm) on deuteron



Polarimetry	0.4
Q^2	0.2
Radiative Corrections	0.2
Event reconstruction	0.2
Statistics	0.3
PDF uncertainty	0.2
Total systematic	0.57
Total statistic and systematic	0.64

- With the wide kinematic coverage and high precision, we will be able to simultaneously fit the two hadronic effects:

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



PVDIS with High Luminosity

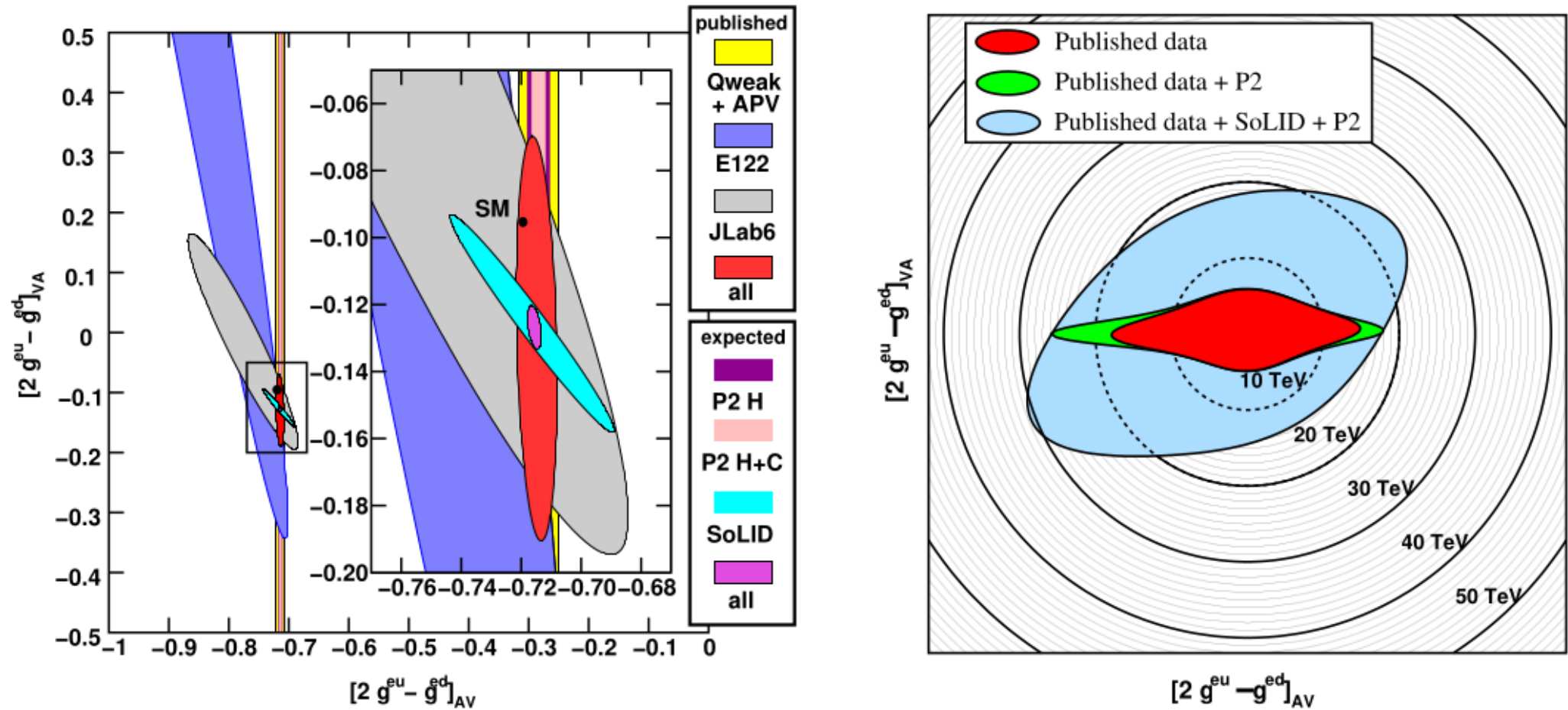


Figure 2: Left panel: Expected limits on the coupling constants from future experiments. Right panel: Projection limits on the scale of BSM physics for SoLID. Definitions are given in Ref.[3].

New Physics Examples from PVDIS – Strong PV

- Parity violation in Strong Interaction

QCD Lagrangian is assumed to be invariant under parity transformation. What implications could the presence of strong P-violation cause to inclusive DIS?

$$xF_{3LU}(x, Q^2) = xF_3^{(\gamma)} - g_V^e \eta_{\gamma Z} xF_3^{(\gamma Z)} + (g_V^e{}^2 + g_A^e{}^2) \eta_Z xF_3^{(Z)}$$

Parton model interpretation:


$$\begin{aligned} F_3^{(\gamma)}(x_B, Q^2) &= 0, \\ F_3^{(\gamma Z)}(x_B, Q^2) &= \frac{1}{\sqrt{1+R^2}} \sum_q 2e_q g_A^q f_1^{(q-\bar{q})}, \\ F_3^{(Z)}(x_B, Q^2) &= \frac{1}{\sqrt{1+R^2}} \sum_q 2g_V^q g_A^q f_1^{(q-\bar{q})}, \end{aligned}$$

slide material from Matteo Cerutti, SoLID
June 2023 collaboration meeting

Bacchetta, Cerutti, Manna, Radici, XZ PLB 849 (2024) 138455

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Parton model interpretation:

Additional contributions due to new PV parton distributions

$$\begin{aligned} \Rightarrow F_3^{(\gamma)}(x_B, Q^2) &= 0, \\ F_3^{(\gamma Z)}(x_B, Q^2) &= \frac{1}{\sqrt{1+R^2}} \sum_q 2e_q g_A^q f_1^{(q-\bar{q})}, \\ F_3^{(Z)}(x_B, Q^2) &= \frac{1}{\sqrt{1+R^2}} \sum_q 2g_V^q g_A^q f_1^{(q-\bar{q})}, \end{aligned}$$

$$\begin{aligned} \Delta F_3^{(\gamma)}(x_B, Q^2) &= -\frac{1}{\sqrt{1+R^2}} \sum_q e_q^2 g_1^{\text{PV}(q+\bar{q})}, \\ \Delta F_3^{(\gamma Z)}(x_B, Q^2) &= -\frac{1}{\sqrt{1+R^2}} \sum_q 2e_q g_V^q g_1^{\text{PV}(q+\bar{q})}, \\ \Delta F_3^{(Z)}(x_B, Q^2) &= -\frac{1}{\sqrt{1+R^2}} \sum_q (g_V^{q2} + g_A^{q2}) g_1^{\text{PV}(q+\bar{q})} \end{aligned}$$

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Parton model interpretation:

Additional contributions due to new PV parton distributions

Quark Polarization

Nucleon Pol.		U	L	T
	U	$f_1(x)$	$g_1^{PV}(x)$	
	L		$g_1(x)$	
	T			$h_1(x)$

How do we look for it?

slide material from Matteo Cerutti, SoLID June 2023 collaboration meeting

Bacchetta, Cerutti, Manna, Radici, XZ PLB 849 (2024) 138455

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Parton model interpretation:

Additional contributions due to new PV parton distributions

→ $F_3^{(\gamma)}(x_B, Q^2) = 0,$

$$F_3^{(\gamma Z)}(x_B, Q^2) = \frac{1}{\sqrt{1+R^2}} \sum_q 2e_q g_A^q f_1^{(q-\bar{q})},$$

$$F_3^{(Z)}(x_B, Q^2) = \frac{1}{\sqrt{1+R^2}} \sum_q 2g_V^q g_A^q f_1^{(q-\bar{q})},$$

$$\Delta F_3^{(\gamma)}(x_B, Q^2) = -\frac{1}{\sqrt{1+R^2}} \sum_q e_q^2 g_1^{\text{PV}(q+\bar{q})},$$

$$\Delta F_3^{(\gamma Z)}(x_B, Q^2) = -\frac{1}{\sqrt{1+R^2}} \sum_q 2e_q g_V^q g_1^{\text{PV}(q+\bar{q})},$$

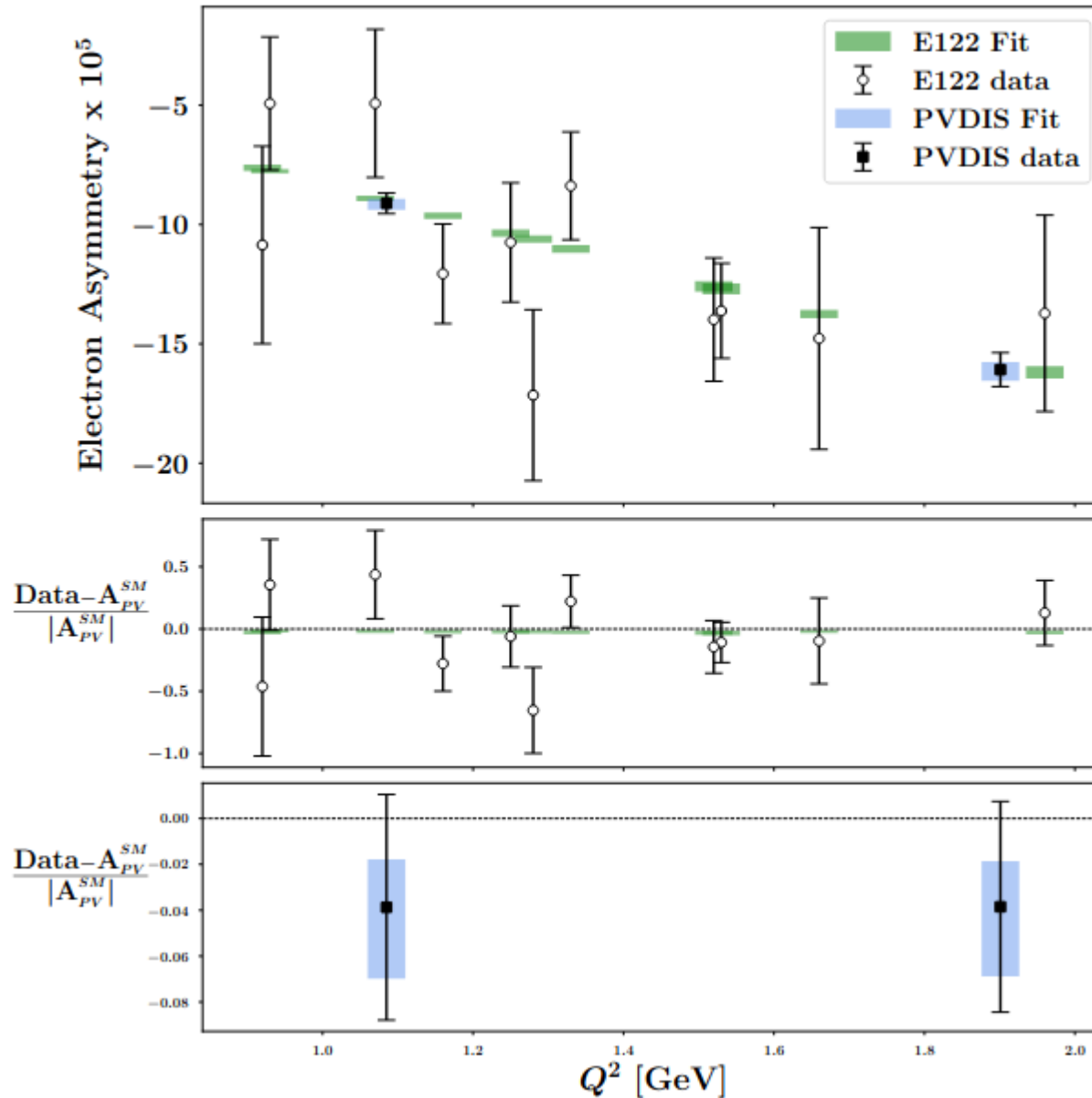
$$\Delta F_3^{(Z)}(x_B, Q^2) = -\frac{1}{\sqrt{1+R^2}} \sum_q (g_V^{q2} + g_A^{q2}) g_1^{\text{PV}(q+\bar{q})}$$

How do we look for it?

Originally we thought we needed positrons. After a couple of months, we realized we can simply use PVDIS Asymmetry!

$$A_{\text{PV}} \equiv \frac{d\sigma(\lambda = 1) - d\sigma(\lambda = -1)}{d\sigma(\lambda = 1) + d\sigma(\lambda = -1)} \quad \text{with} \quad g_1^{\text{PV}}(x) = \alpha g_1(x)$$

New Physics Examples from PVDIS – Strong PV



$$g_1^{PV}(x) = \alpha g_1(x)$$

Baseline:

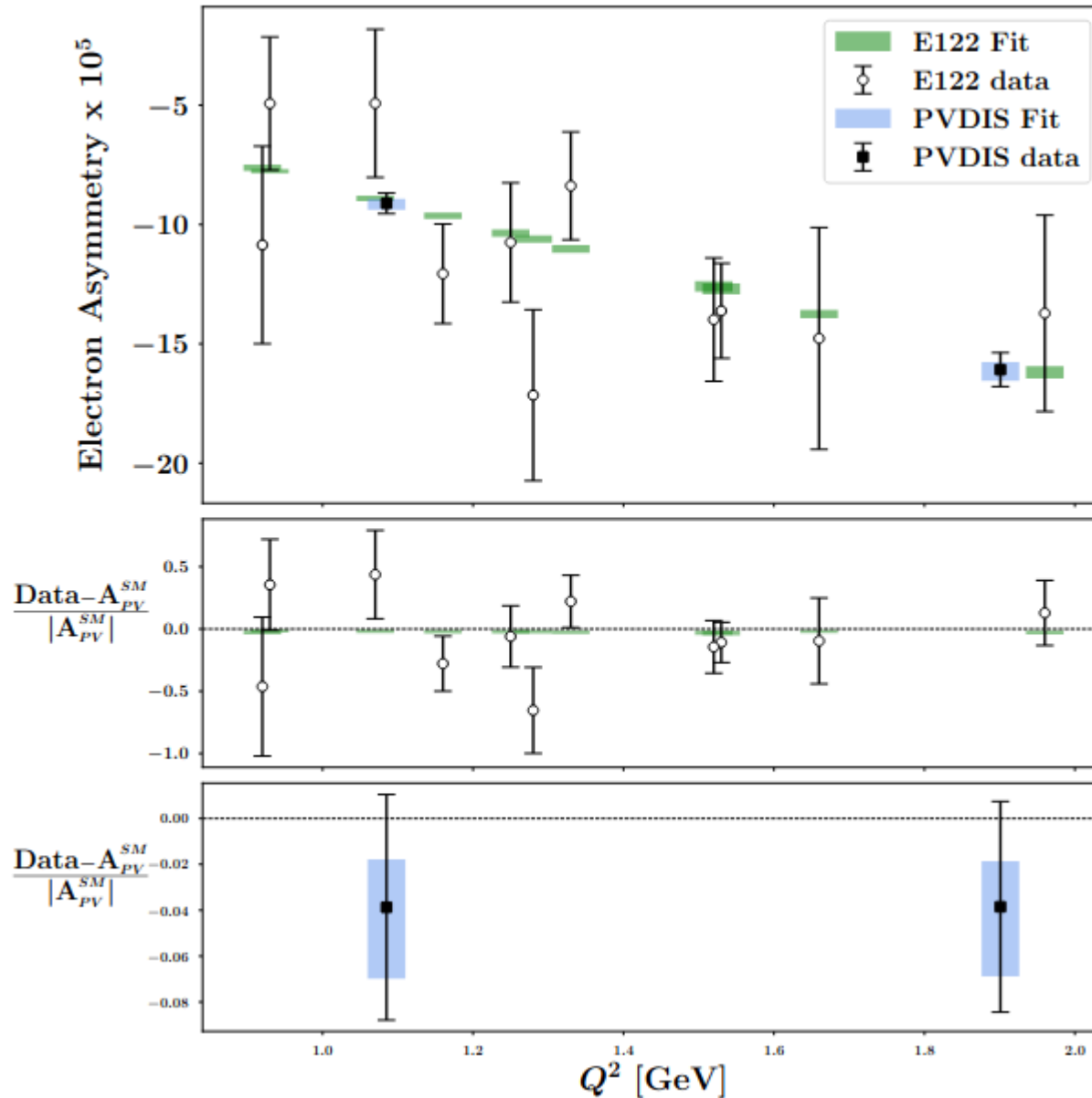
$$\alpha = (-1.01 \pm 0.66) \times 10^{-4}$$

If true, this would indicate there are more left-handed than right-handed quarks in an unpolarized nucleon, i.e. that parity symmetry is slightly broken in the structure of the nucleon.

slide material from Matteo Cerutti, SoLID
June 2023 collaboration meeting

Bacchetta, Cerutti, Manna, Radici, XZ PLB 849 (2024) 138455

New Physics Examples from PVDIS – Strong PV



$$g_1^{PV}(x) = \alpha g_1(x)$$

Baseline:

$$\alpha = (-1.01 \pm 0.66) \times 10^{-4}$$

With SoLID (d):

$$\alpha = (-1.01 \pm 0.21) \times 10^{-4}$$

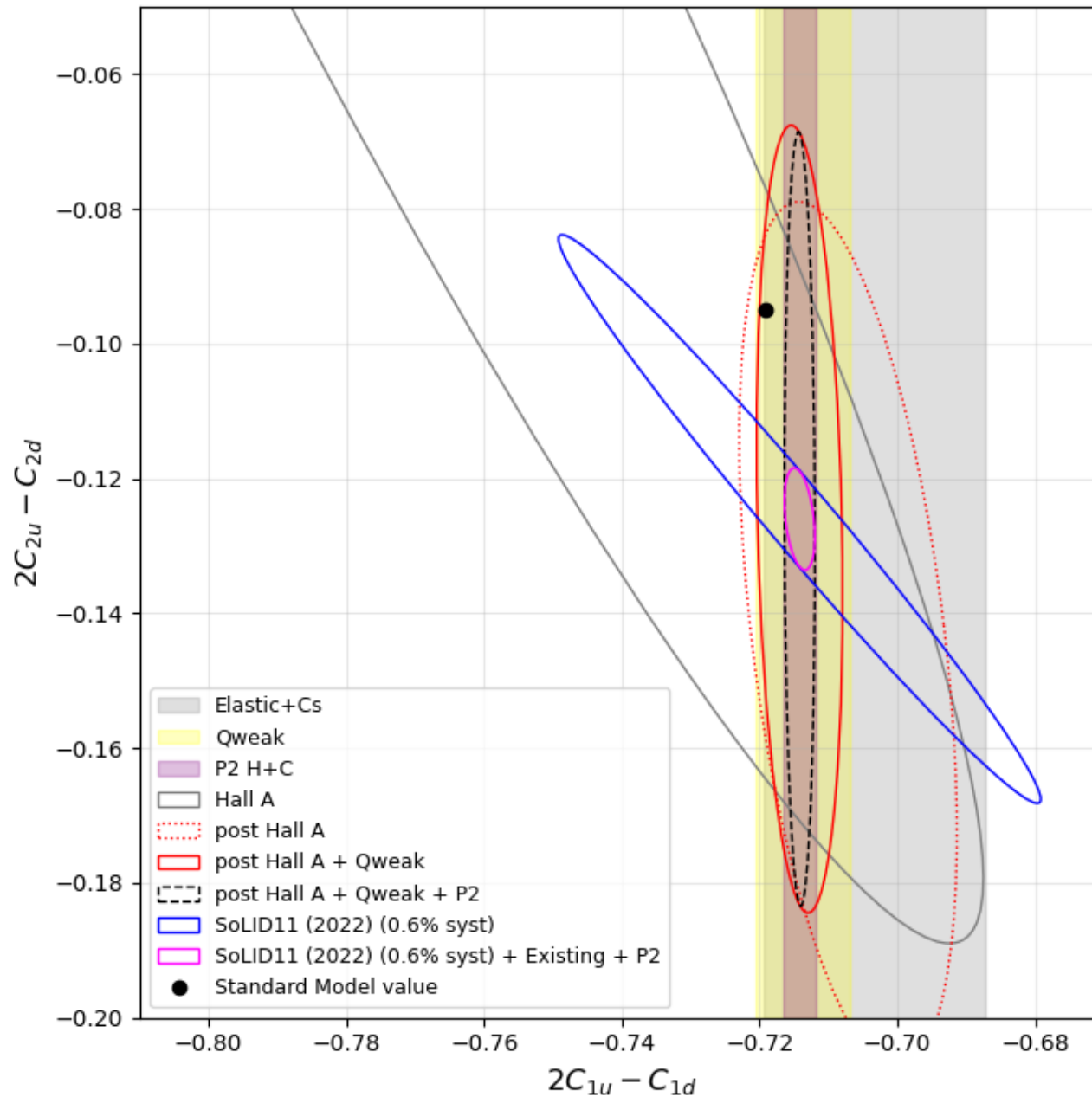
With SoLID (p):

$$\alpha = (-1.01 \pm 0.15) \times 10^{-4}$$

slide material from Matteo Cerutti, SoLID
June 2023 collaboration meeting

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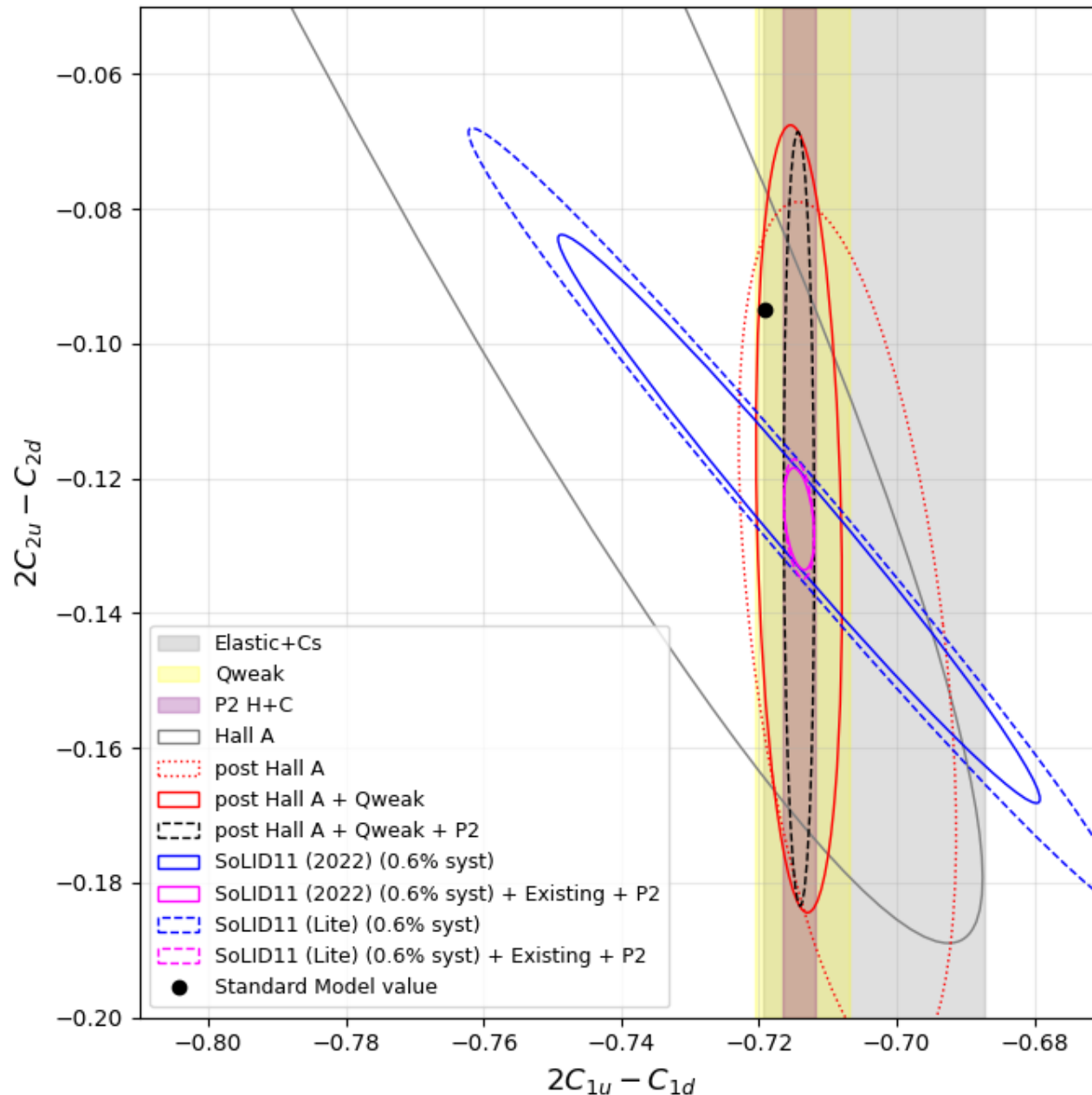
PVDIS with High Luminosity – 2022 version



Polarimetry	0.4
Q^2	0.2
Radiative Corrections	0.2
Event reconstruction	0.2
Statistics	0.3
PDF uncertainty	0.2
Total systematic	0.57
Total statistic and systematic	0.64

- In preparation for PAC50 and LRP, we carried out extensive study taking into account PDF uncertainties and hadronic effects.
- Our fitted ellipse (from the 4-param fit) is slightly larger than Jens'.
- Note that SoLID approaches ~ -1 slope (max)

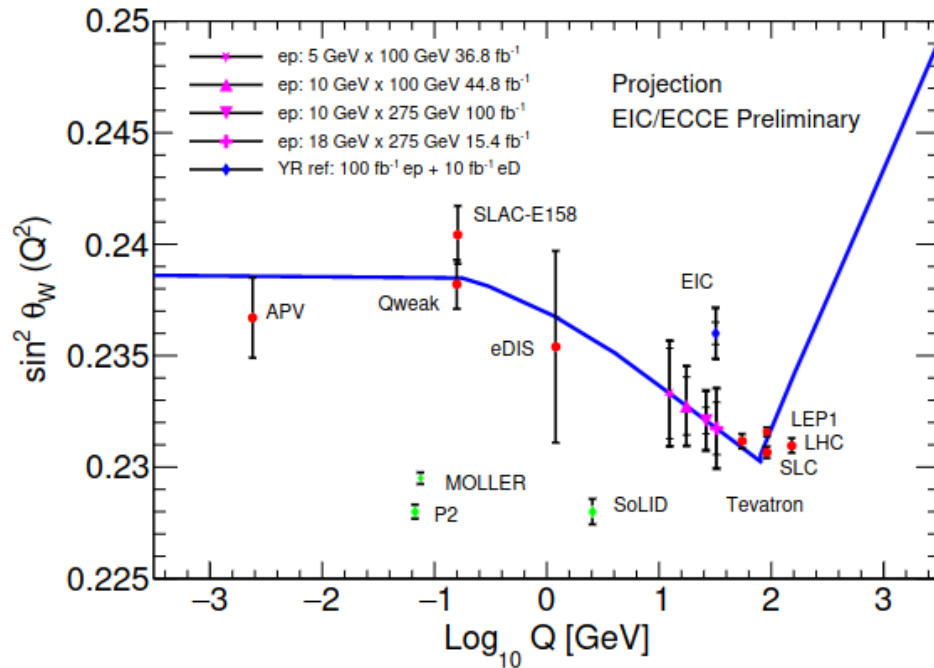
PVDIS with High Luminosity – 2026 “Lite”



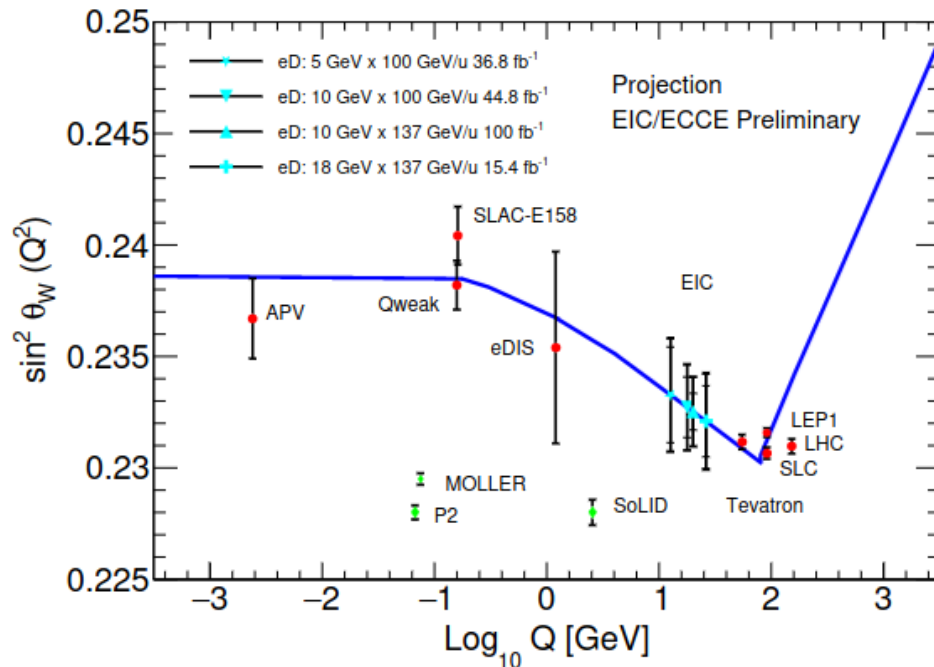
Polarimetry	0.4
Q^2	0.2
Radiative Corrections	0.2 $\leftarrow \times \sqrt{2}$
Event reconstruction	0.2
Statistics	0.3 $\leftarrow \times \sqrt{2}$
PDF uncertainty	0.2
Total systematic	0.57
Total statistic and systematic	0.64

- “SoLID lite” ellipse “grew” by 40%, but the combined uncertainty on C2 only increased 20%

PVDIS with EIC



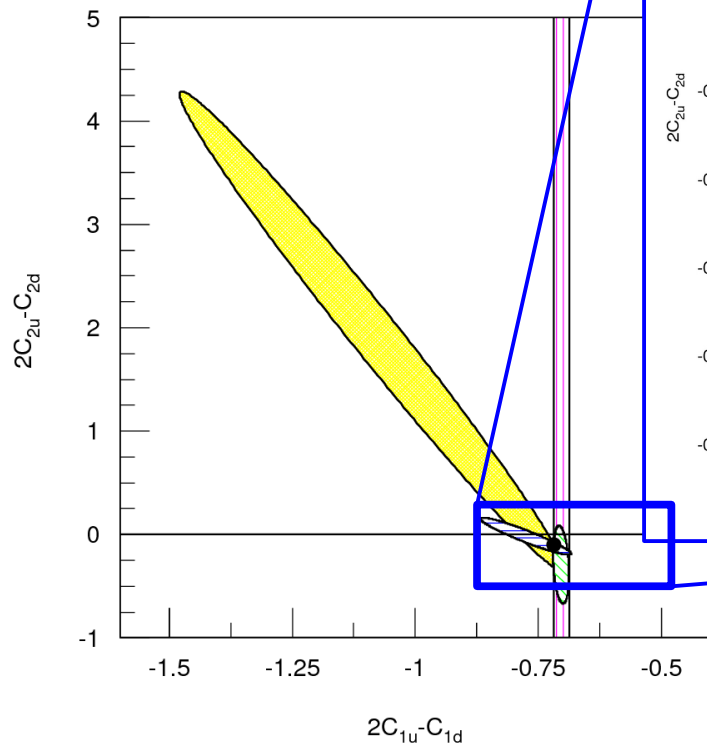
- C1, C2's are low-energy couplings, whether we can determine their value at EIC energy is to be discussed



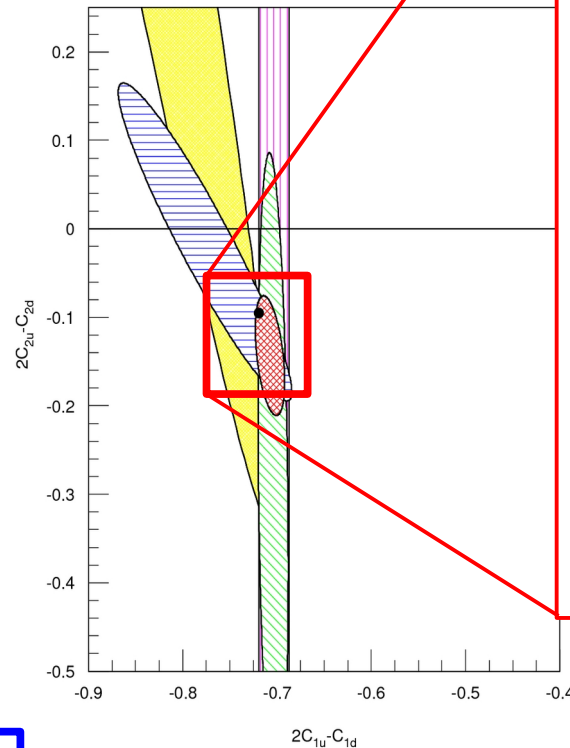
Boughezal et al, PRD106(2022), 1, 016006

Pioneer → Exploratory → High-Lumi (Precision)

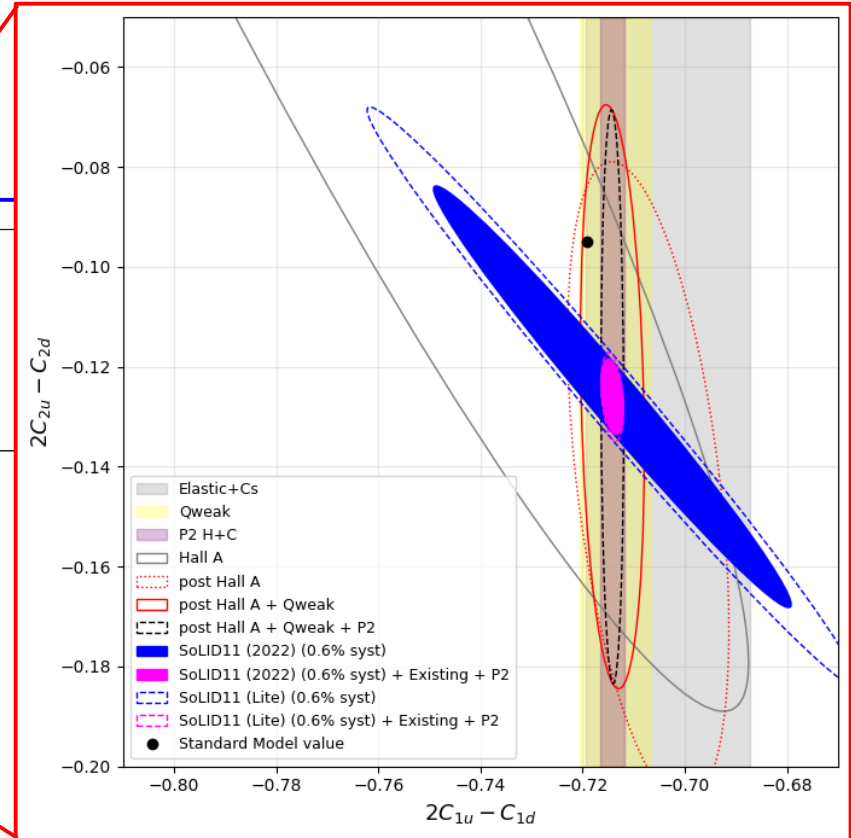
- E122 – 1978
- + SAMPLE + Cs + TI



- Hall A – 2014
- + Qweak



- High Luminosity – 20??
- + P2



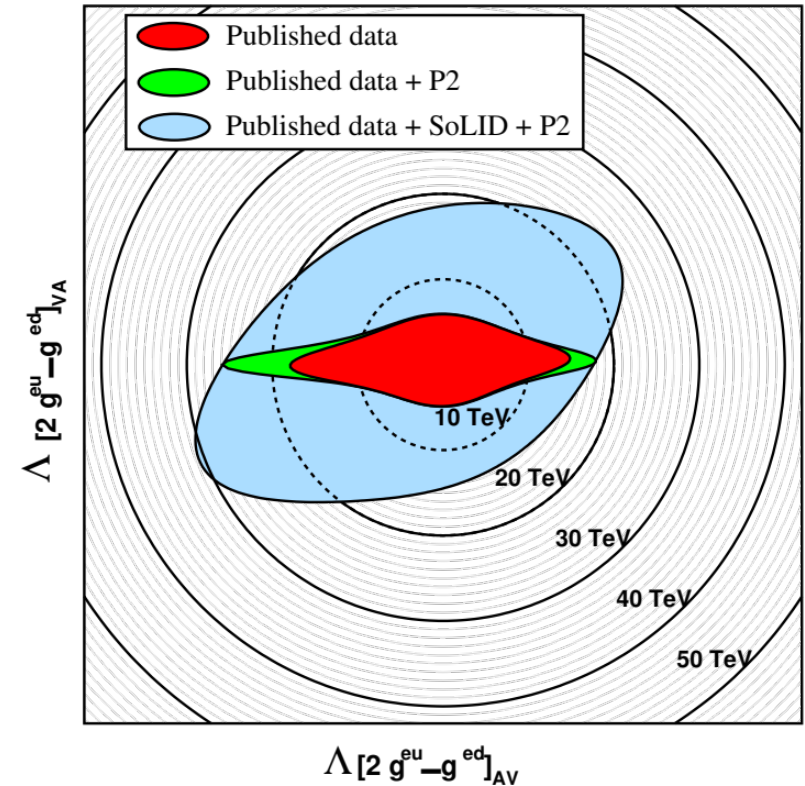
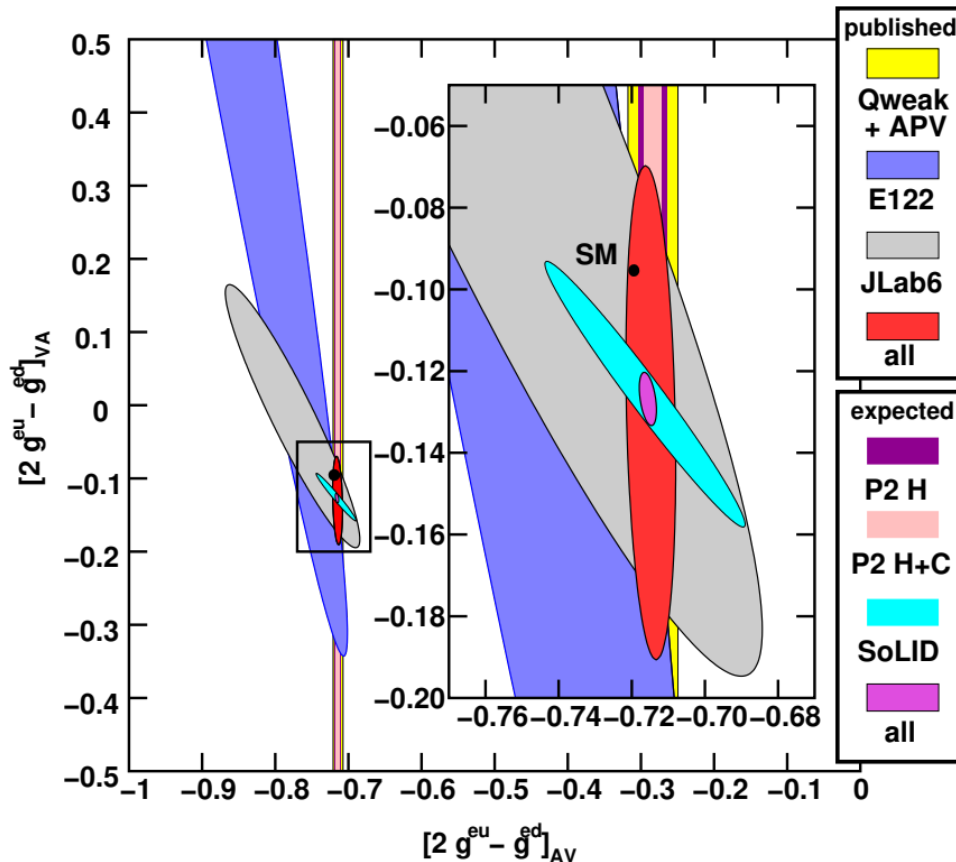
Backup Slides

SoLID for JLab Hall A – Parity-Violating DIS

- BSM Physics has large phase space, precision measurements would point the way
- PVDIS deuteron measurement access effective electron-quark couplings

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

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

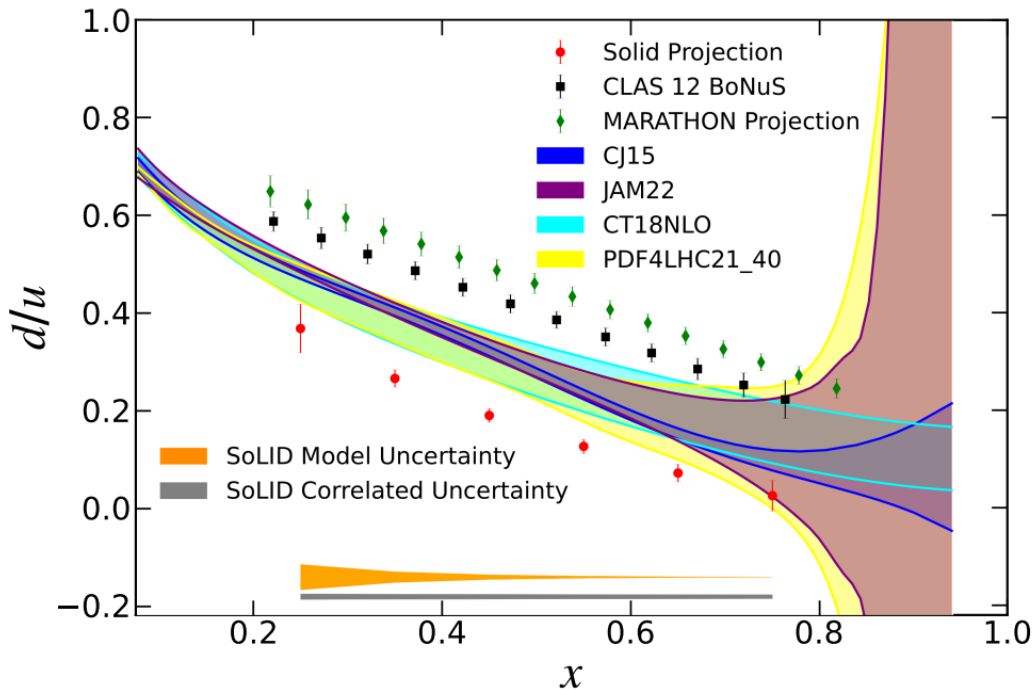


$$\frac{G_F}{\sqrt{2}} g_{ij} \rightarrow \frac{G_F}{\sqrt{2}} g_{ij} + \eta_{ij}^q \frac{4\pi}{(\Lambda_{ij}^q)^2}$$

SoLID for JLab Hall A – Parity-Violating DIS

- PVDIS proton measurement access
PDF d/u at high x, without the need of nuclear model

$$A_{RL,p}^{\text{DIS}} \approx \frac{1}{4\pi\alpha} \frac{Q^2}{v^2} \left[\frac{12 g_{AV}^{eu} - 6 g_{AV}^{ed} d/u}{4 + d/u} \right]$$



Figures from SoLID 2022 WP

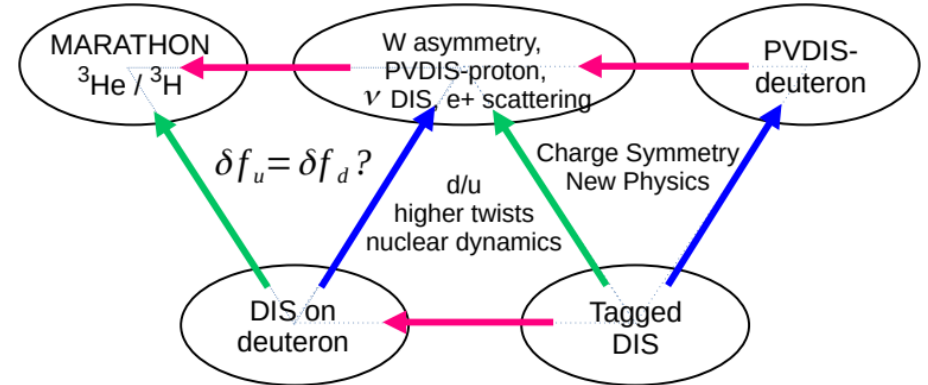
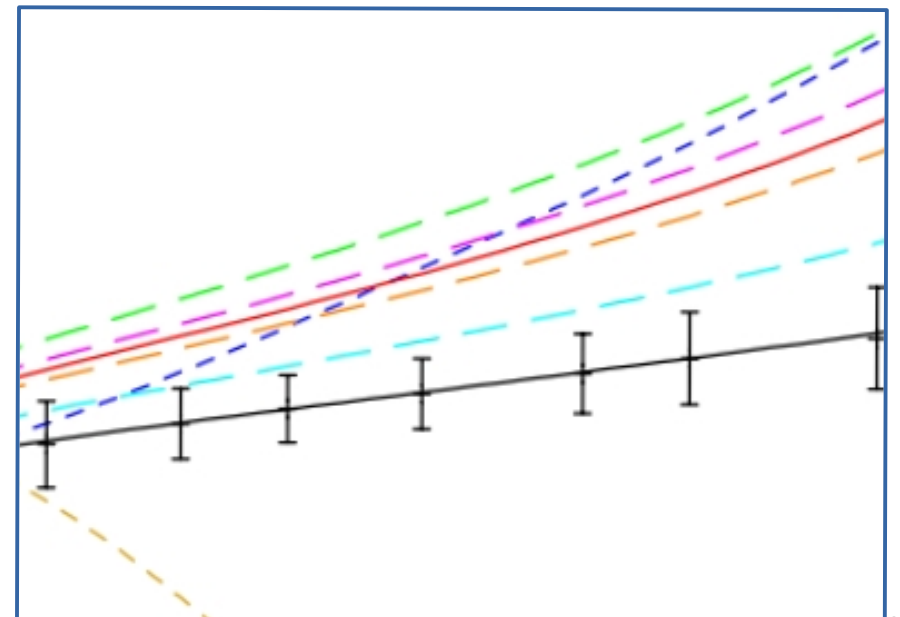


Figure from A. Accardi,
INT workshop on PVDIS at JLab 12 GeV (2022)

- PVDIS ^{48}Ca access flavor dependence of EMC effect $\frac{9}{2}u_A^+ - d_A^+$

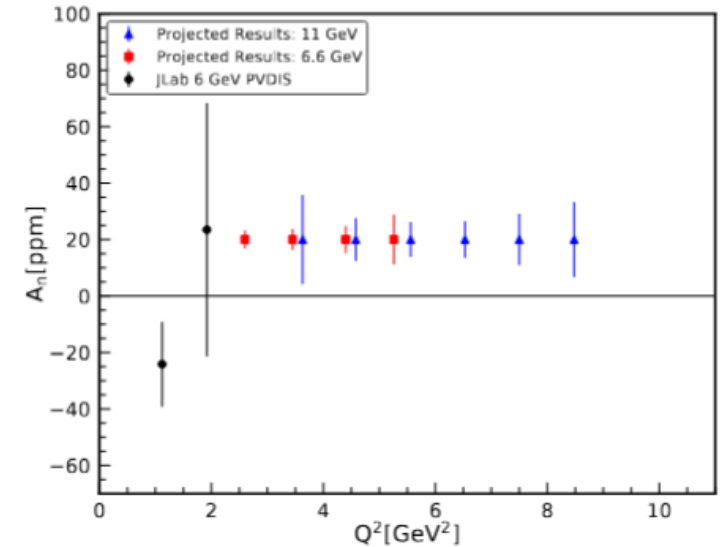
$$a_1 \simeq \frac{9}{5} - 4 \sin^2 \theta_W - \frac{12}{25} \frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$



BNSSA and DDVCS

- Beam Normal Single Spin Asymmetry (E12-22-004)
 - Approved with A- rating
 - Investigate the effect of two-photon exchange in DIS
 - Q² dependence of the asymmetry

$$A_{\text{raw}} = \frac{1}{P_b} \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$



- Double Deeply Virtual Compton Scattering (C12-25-010)

