Parity Violating DIS at 22 GeV with SoLID

Michael Nycz

Special Thanks to
Matteo Cerutti and Richard Whitehill,
Xiaochao Zheng, and the SoLID
Collaboration

UNIVERSITY of VIRGINIA

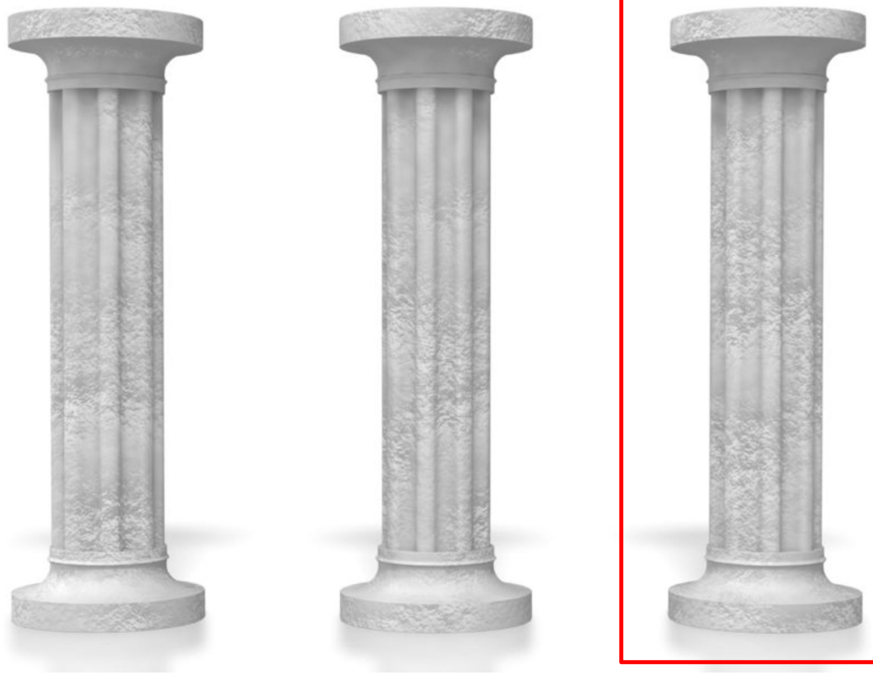
SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

Three Pillars of the SoLID Program

SIDIS ***J/Ψ*** ***PVDIS***

Three Pillars of the SoLID Program

SIDIS **J/Ψ** ***PVDIS***

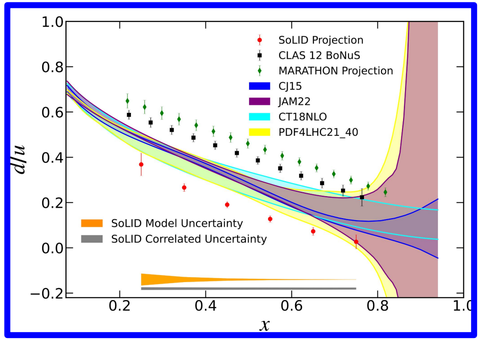


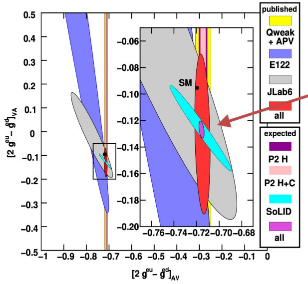
SoLID PVDIS 11 GeV Program

1. **Parity Violating DIS on Isoscalar Deuteron**
   a. Precision determination of electroweak parameters
   b. Beyond-the-Standard Model (BSM) physics search
2. **Parity Violating DIS on Proton Target**
   a. *d/u* measurement
3. **Parity Violating EMC Effect**
   a. Isospin dependence of the EMC effect by the use of neutron-rich isotopes

SoLID PVDIS 11 GeV Program

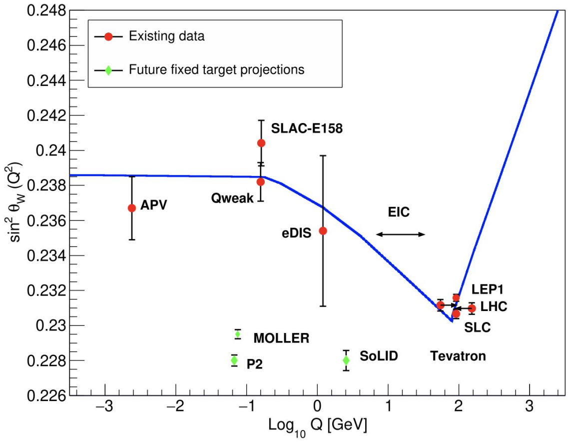
1. **Parity Violating DIS on Isoscalar Deuteron**
   a. Precision determination of electroweak parameters
   b. Beyond-the-Standard Model (BSM) physics search
2. **Parity Violating DIS on Proton Target**
   a. *d/u* measurement
3. **Parity Violating EMC Effect**
   a. Isospin dependence of the EMC effect by the use of neutron-rich isotopes





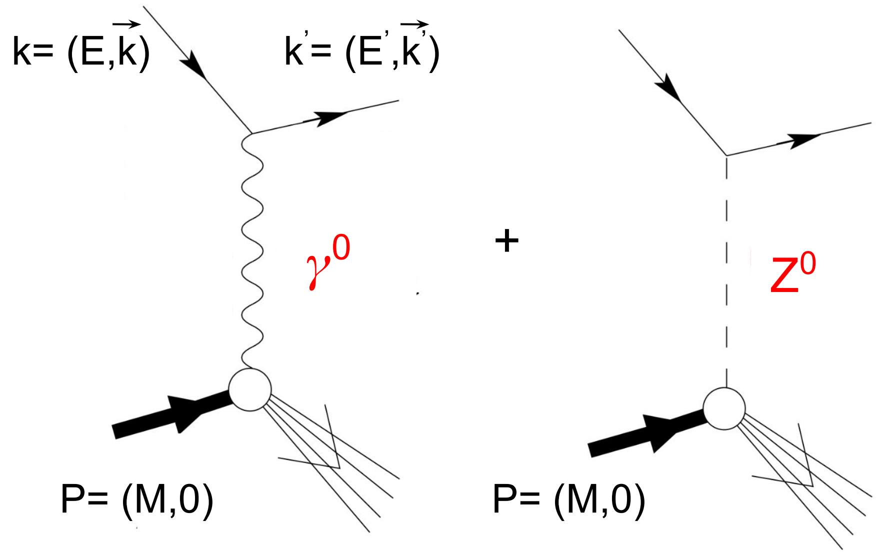
Qweak, APV, and P2 do not provide constraints in the vertical direction. Only PVDIS experiments (SLAC, Jlab 6 GeV, and Solid) constrain the C_2's

Paul Sauder, Paul Reimer, & Xiaochao Zheng (PAC 50)



SoLID PVDIS Program: Isoscalar Deuteron

$$A_{PV}^{(e)} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{d\sigma_e}{d\sigma_0}$$



In Deep Inelastic Scattering regime

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}[a_1 + a_3 Y]$$

$$a_1(x) = 2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \qquad a_3(x) = g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}}$$

+

Isoscalar Deuteron Target

$$A_{PV,(d)}^{SM} = \frac{3G_F Q^2}{10\sqrt{2}\pi\alpha}\left[(2g_{AV}^{eu} - g_{AV}^{ed}) + R_V Y(2g_{VA}^{eu} - g_{VA}^{ed})\right]$$

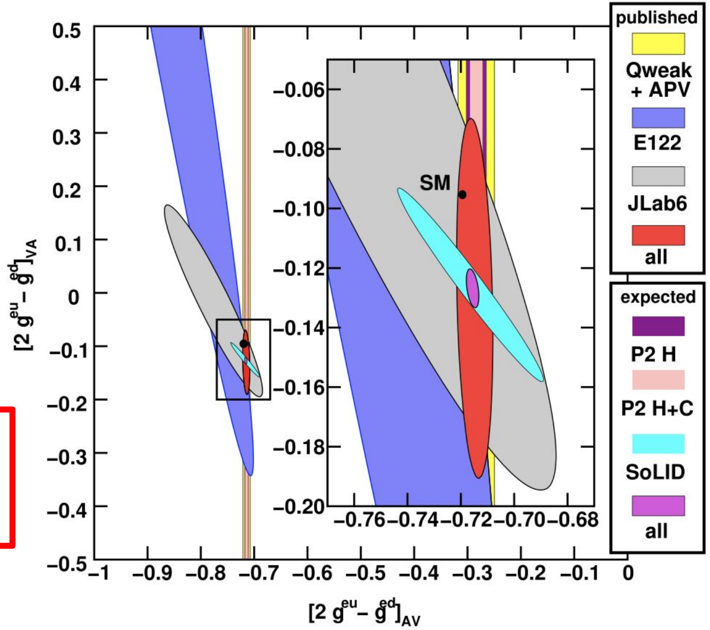
SoLID PVDIS Program: Isoscalar Deuteron

- Full exploration of BSM physics
  - need lepton-lepton or lepton-quark interactions

SoLID PVDIS

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

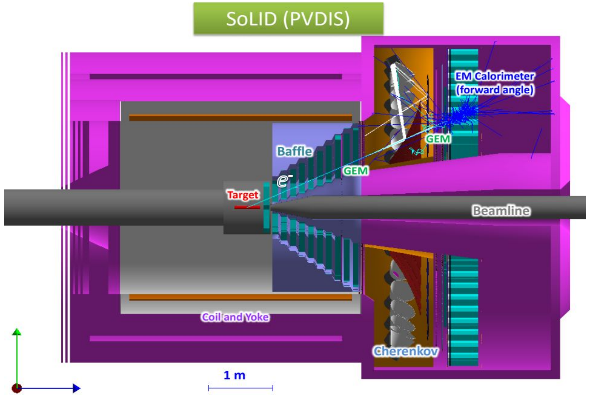
$$A_{PV,(d)}^{SM} = \frac{3G_FQ^2}{10\sqrt{2}\pi\alpha}\left[(2g_{AV}^{eu} - g_{AV}^{ed}) + R_VY(2g_{VA}^{eu} - g_{VA}^{ed})\right]$$

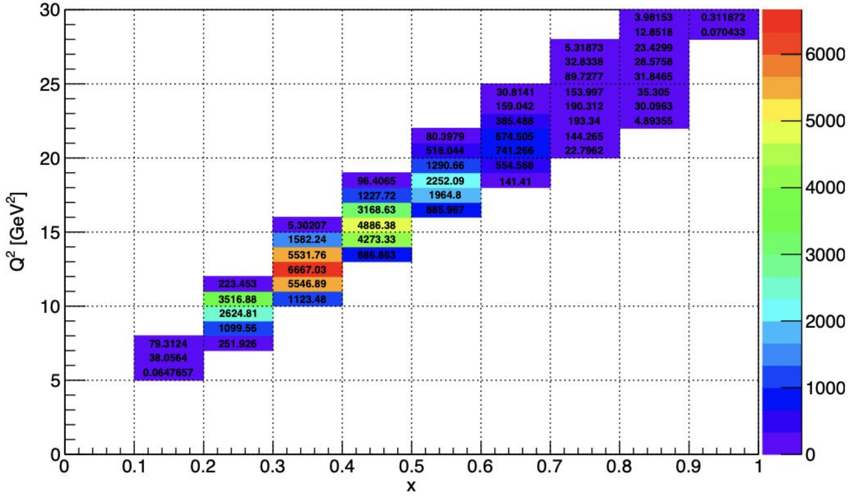


Simultaneous fit of $(2g_{AV}^{eu} - g_{AV}^{ed})$ and $(2g_{VA}^{eu} - g_{VA}^{ed})$.

SoLID PVDIS 22 GeV Program

- 50 μA e^- beam incident on 40cm liquid deuterium target
- Scaled by trigger efficiency
- DIS kinematic cut: W > 2
- Acceptance cut for nominal target position (z = 10cm): 22° < θ < 35°





Rates (Hz) at 22 GeV

Uncertainties: Statistical and (Experimental) Systematics

- Statistical uncertainty

$$\rightarrow \quad dA_{PV}^{\mathrm{stat}} = \frac{1}{P_e \sqrt{n_b}} = \sigma_{\mathrm{stat},b}$$

Beam polarization = 85%

120 days

- Experimental systematic uncertainties

Source	Relative Uncertainty dA/A
Beam polarization	0.4%
Q^2 determination	0.2%
Event reconstruction	0.2%
Radiative correction	0.2%

Completely correlated ($\sigma_{\mathrm{corr}}/A = 0.45\%$)

Uncorrelated ($\sigma_{\mathrm{uncorr}}/A = 0.28\%$)

PDF Uncertainties

- PDF uncertainties were determined following the prescription of each PDF set
- Hessian PDF Sets

$$\left(\Sigma^2_{\mathrm{PDF}}\right)_{bb'} = \frac{1}{4}\sum_{m=1}^{N_{\mathrm{PDF}}/2}\left(A_{2m,b} - A_{2m-1,b}\right)\left(A_{2m,b'} - A_{2m-1,b'}\right)$$

- Replica PDF Sets

$$\left(\Sigma^2_{\mathrm{PDF}}\right)_{bb'} = \frac{1}{N_{\mathrm{PDF}}}\sum_{m=1}^{N_{\mathrm{PDF}}}\left(A_{m,b} - A_{0,b}\right)\left(A_{m,b'} - A_{0,b'}\right)$$

<u>PDF Uncertainty Matrix</u>

Accounted for both diagonal and off-diagonal elements of PDF uncertainty

$$\Sigma^2_{pdf} = \begin{bmatrix} \sigma^2_{1,pdf} & \sigma_{1,pdf}\sigma_{2,pdf} & \cdots & \sigma_{1,pdf}\,\sigma_{N_{bin},pdf} \\ & \sigma^2_{2,pdf} & \cdots & \sigma_2\sigma_{N_{bin},pdf} \\ & & \ddots & \vdots \\ & & & \sigma^2_{N_{bin},pdf} \end{bmatrix}$$

Fitting Procedure

1. Generate Pseudo data

$$(A_{\mathrm{PV}})_b^{\mathrm{pseudo}} = (A_{\mathrm{PV}})_b^{\mathrm{SM}} + r_b\sqrt{\sigma^2_{\mathrm{stat},b} + \left[(A_{\mathrm{PV}})_b^{\mathrm{SM}}\frac{\sigma_{\mathrm{uncorr}}}{A}\right]^2_b} + r'(A_{\mathrm{PV}})_b^{\mathrm{SM}}\left(\frac{\sigma_{\mathrm{corr}}}{A}\right)_b$$

2. Preform χ^2 minimization

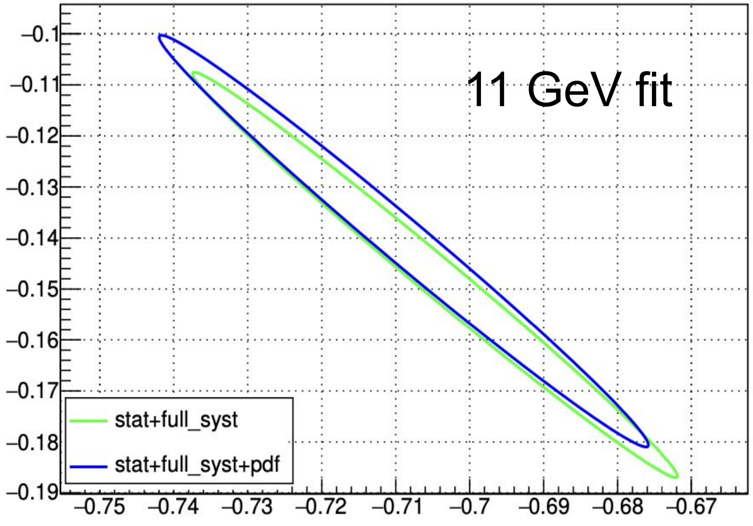
$$\chi^2 = [\mathcal{A}^{\mathrm{pseudo}} - \mathcal{A}^{\mathrm{fit}}][(\Sigma^2)^{-1}][\mathcal{A}^{\mathrm{pseudo}} - \mathcal{A}^{\mathrm{fit}}]^T$$

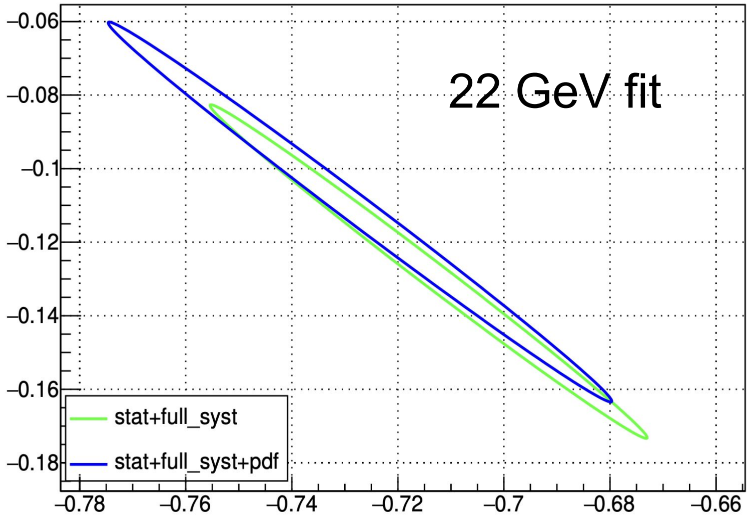
Where

$$(A_{\mathrm{PV}})_b^{\mathrm{fit}} = (A_{\mathrm{PV}})_b^{\mathrm{SM}}\left[\sin^2\theta_W\right]\left(1 + \frac{\beta_{\mathrm{HT}}}{(1-x)^3 Q^2} + \beta_{\mathrm{CSV}}x^2\right)$$

$$[C_{1q}, C_{2q}]$$

SoLID PVDIS Program: Isoscalar Deuteron





$$2C_{2u} - C_{2d} \text{ vs. } 2C_{1u} - C_{1d}$$

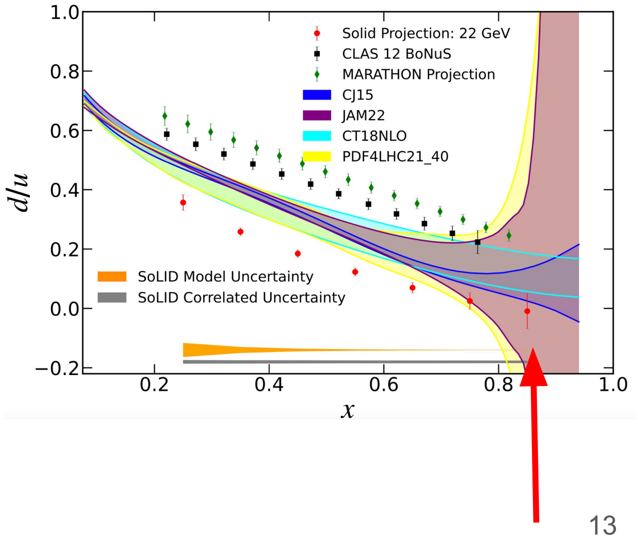
22 GeV best fit provides a ~10% reduction in vertical constraint vs 11 GeV

SoLID PVDIS 22 GeV Program: Proton

Proton measurement

- Lack of free neutron target
  - Nuclear corrections in the deuteron (large uncertainties)
  - Measurement of d/u → challenging at high x
- BoNuS (**Barely** Off-Shell Neutron Structure)
- MARATHON (Ratio of A=3 mirror nuclei)
- SoLID PVDIS on the **Proton**
  - d/u obtained free nuclear effects

$$A_{PV,(p)} = \frac{3G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{\left(2g_{AV}^{eu} - \frac{d}{u}g_{AV}^{ed}\right) + Y\left[2g_{VA}^{eu} - \frac{d}{u}g_{VA}^{ed}\right]}{4 + \frac{d}{u}}$$



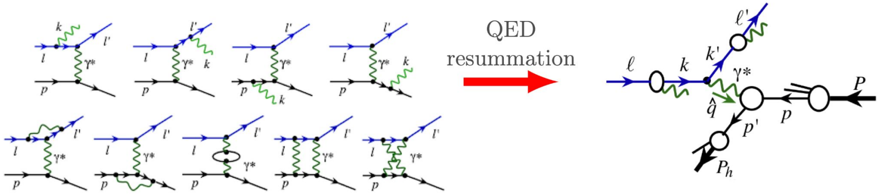
SoLID PVDIS Strange Quark

PVDIS analysis utilizing a joint QED-QCD framework

➔ Information on the nucleon's light sea and **strange content**

Advantages of 22 GeV measurement:

1. Higher Q^2 suppresses power corrections
2. Expands the x region suitable for analysis within a joint QED+QCD factorization framework

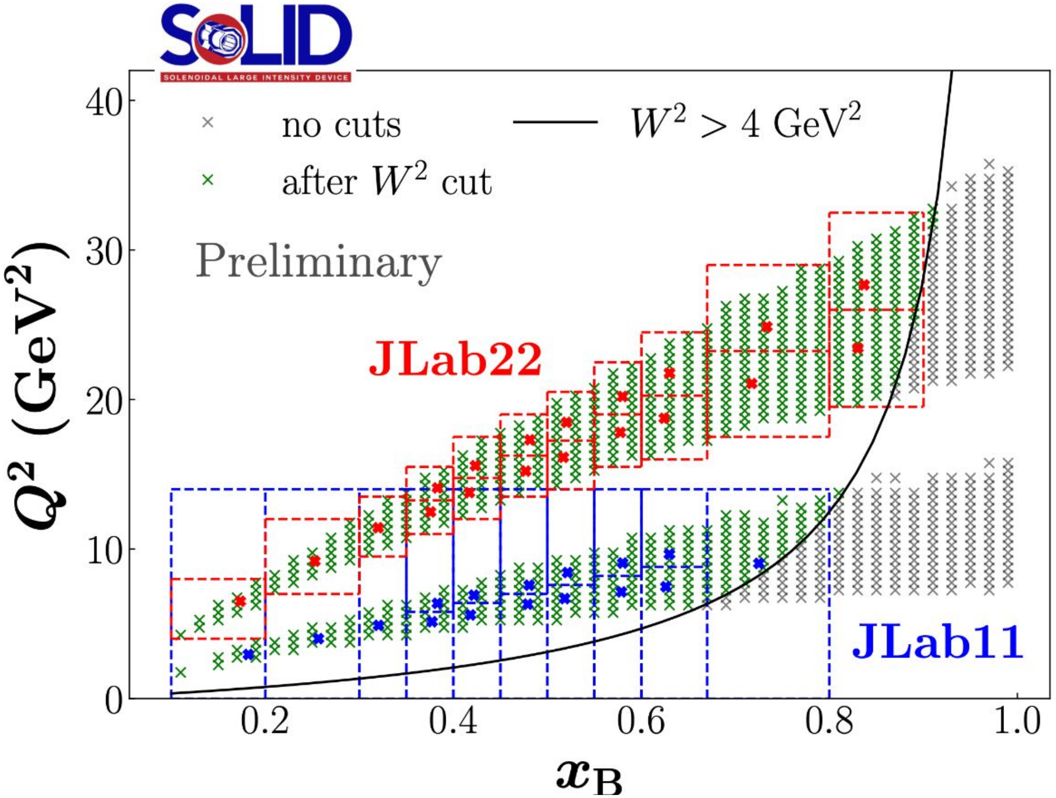


T. Liu, W. Melnitchouk, J. Qiu, N. Sato JHEP 11 (2021)

$$\frac{\mathrm{d}\sigma_{(U/L)U}}{\mathrm{d}x_B\,\mathrm{d}y} = \int_{\zeta_{\min}}^{1} \frac{\mathrm{d}\zeta}{\zeta^2} \underbrace{D_{e/e}(\zeta,\mu^2)}_{\text{LFF}} \int_{\xi_{\min}}^{1} \mathrm{d}\xi\, \underbrace{f_{e/e}(\xi,\mu^2)}_{\text{LDF}} \left[\frac{Q^2}{x_B}\frac{\hat{x}_B}{\hat{Q}^2}\right] \frac{\mathrm{d}\hat{\sigma}_{(U/L)U}}{\mathrm{d}\hat{x}_B\,\mathrm{d}\hat{y}}$$

R. Whitehill, M. M. Dalton, T. Liu, W. Melnitchouk, J. Qiu, and N. Sato

SoLID PVDIS Strange Quark



Scenarios:

1. statistical uncertainties + experimental systematics
2. (1) + QED effects
3. (2) + HT effects

Note:

→ $P = 85\%$

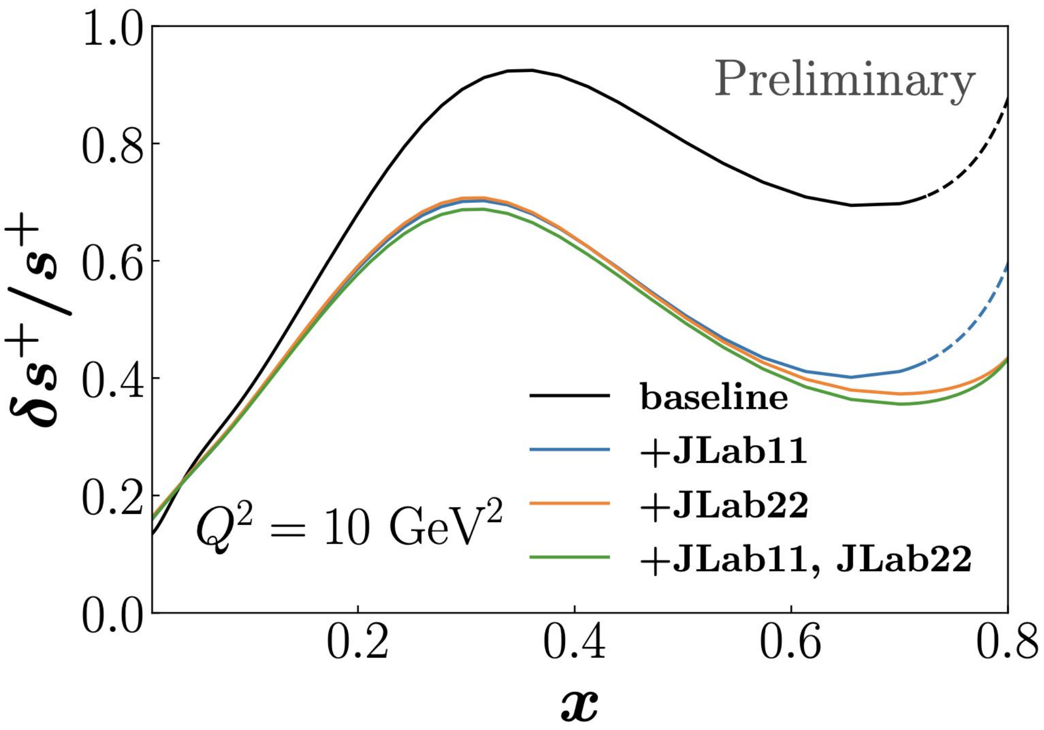
→ $d\mathcal{L}/dt = 4.85 \times 10^{38}$ cm^{-2} s^{-1}

→ run time: 50 days/target

→ $\delta^{\rm syst} A_{\rm PV} = 0.5\%$

R. Whitehill, M. M. Dalton, T. Liu, W. Melnitchouk, J. Qiu, and N. Sato

SoLID PVDIS Strange Quark Projections

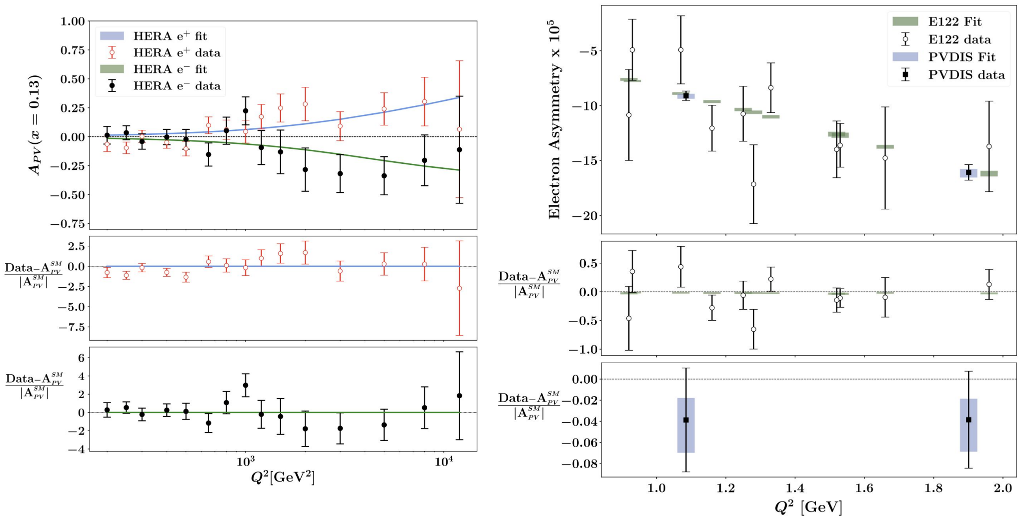


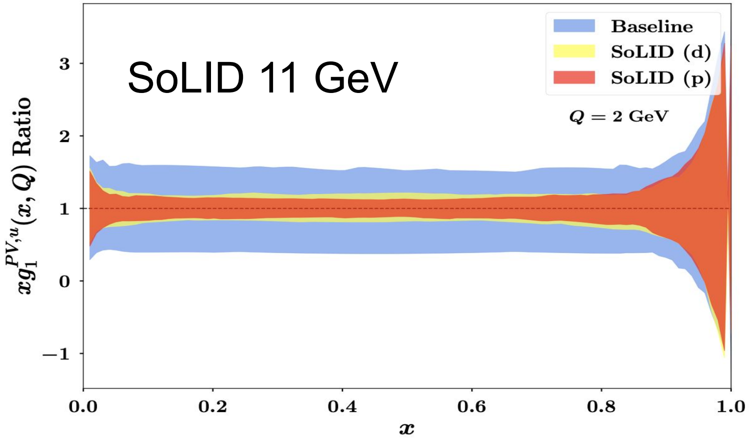
$s+ = s + \bar{s}$

Richard Whitehill, SoLID Opportunities and Challenges (2024)

New Possibilities to Explore for 22 GeV: Strong PV

- Proton internal structure in mirrored world
  - QCD → invariant under Parity transformation
  - Parity conservation in strong interactions → not guaranteed



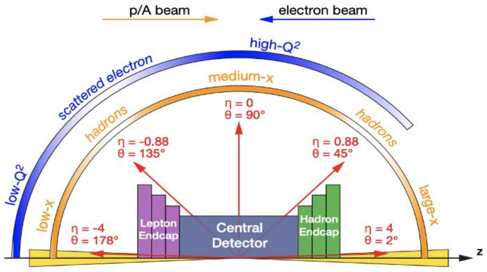


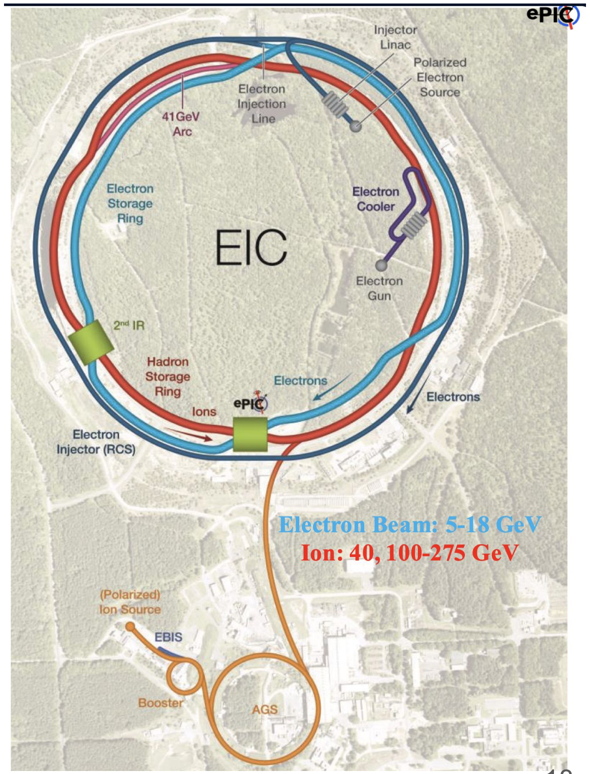
SoLID PVDIS will make the largest impact

Alessandro Bacchetta, Matteo Cerutti, Ludovico Manna, Marco Radici, and Xiaochao Zheng

Weak Mixing Angle at the EIC

- High luminosity machine
  - (10^{33} - 10^{34} cm^{-2} s^{-1})
- Large center-of-mass energy range
  - √21-140 GeV
- Polarized e^-, protons and light ions beams
  - ≥70%
- Ions beam from deuteron to heavier nuclei
  - Gold, lead, or uranium





Settings

Electron Energy [GeV]	Proton Energy [GeV]	Annual Luminosity [fb^{-1}]		Electron Energy [GeV]	Deuteron Energy [GeV]	Annual Luminosity [fb^{-1}]
5	41	4.4		5	41	4.4
5	100	36.8		5	100	36.8
10	100	44.8		10	100	44.8
10	275	100		10	137	100
18	275	15.4		18	137	15.4
18	275	100				

Extraction of the Weak Mixing Angle at the EIC

$$A_{RL}^{e^-} = \frac{|\lambda|\eta_{\gamma Z}\left[g_A^e 2yF_1^{\gamma Z} + g_A^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_V^e(2-y)F_3^{\gamma Z}\right]}{2yF_1^{\gamma} + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma} - \eta_{\gamma Z}\left[g_V^e 2yF_1^{\gamma Z} + g_V^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_A^e(2-y)F_3^{\gamma Z}\right]}$$

- Extraction of $\sin^2\theta_W$ from minimization of the χ^2

$$\chi^2 = \left[A^{pseudo-data} - \boldsymbol{A^{theory}}\right]^T (\Sigma^2)^{-1}\left[A^{pseudo-data} - \boldsymbol{A^{theory}}\right]$$

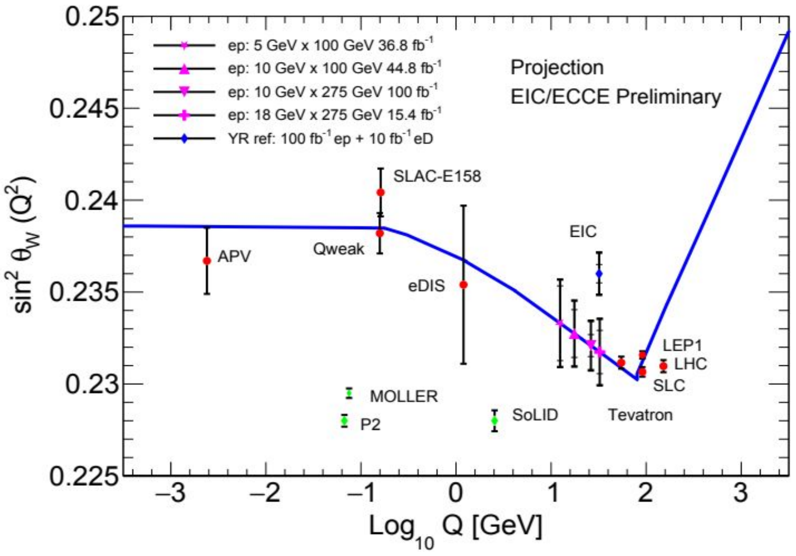
- $\boldsymbol{A^{theory}}$ is a function of $\sin^2\theta_W$ via the weak neutral couplings
- Single parameter fit to extract → $\boldsymbol{\sin^2\theta_W}$

Uncertainty Matrix

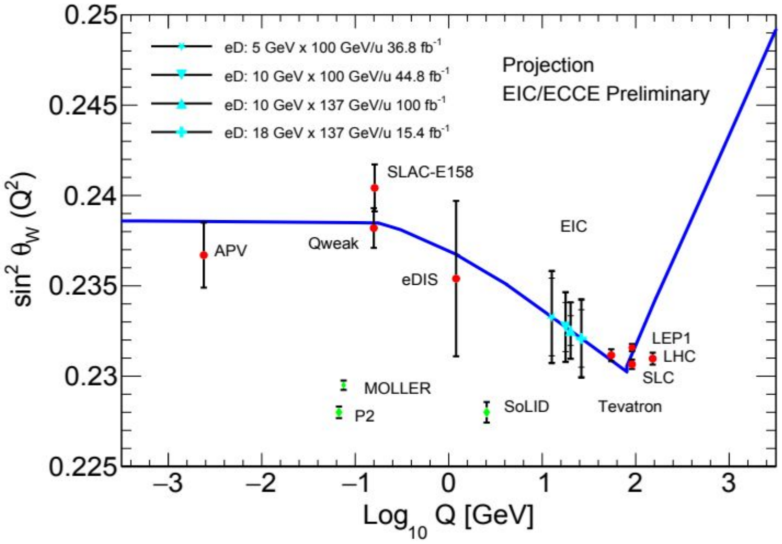
$$(\Sigma^2)_{bb'} = (\Sigma_0^2)_{bb'} + (\Sigma_{pdf}^2)_{bb'}$$

R. Boughezal et al., Neutral-current electroweak physics and SMEFT studies at the EIC, Phys. Rev. D

ep Results



eD Results

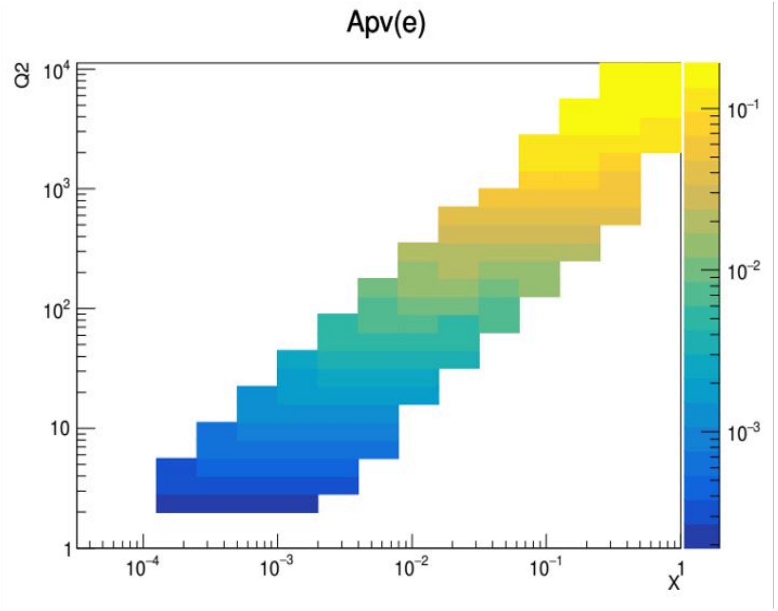


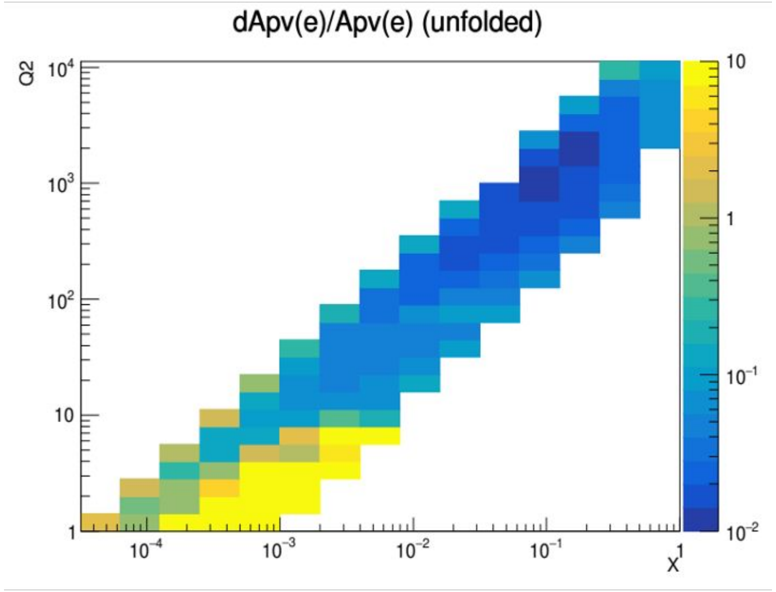
Statistical and beam polarimetry uncertainties dominate;
moderate precision in an **unmeasured energy region**, multi-year run would help
Combining ep + eD results, approach the sensitivity of Yellow Report: ~±0.00097

Summary and Outlook

- SoLID PVIDS has a strong 11 GeV program
  - Precision measurements of electroweak parameters
  - d/u
- SoLID PVIDS at 22 GeV could expand
- Exciting new studies using measured A_{pv} of SoLID at 22 GeV
  - Explore s^+
  - Search for strong PV
- At the EIC / ePIC
  - Can measure $\sin^2(\theta)$ in an unmeasured energy range
  - Bridging region between fixed target and collider experiments

EIC Kinematic range



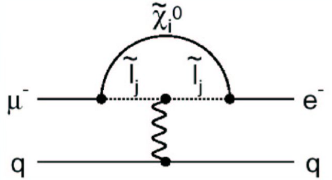


Charged Lepton Flavor Violation

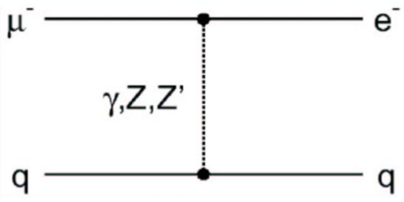
- ❖ Neutrino oscillations
  - ➢ Provided evidence for lepton flavor violation
- ❖ No experimental evidence for flavor violation in charged lepton sector
- ❖ Predicted CLFV branching ratio
  - ➢ Br($\mu \rightarrow e\gamma$) < 10^{-54}
- ❖ Example: Supersymmetry prediction
  - ➢ Br($\mu \rightarrow e\gamma$) ~ 10^{-15}
- ❖ Br($\mu \rightarrow e\gamma$) < 10^{-13} : Current limit (MEG experiment)
  - ➢ Baldini, A.M., Bao, Y., Baracchini, E. et al. Eur. Phys. J. C 76, 434
- ❖ $e \rightarrow \tau$ transition constraints - much weaker
  - ➢ Br($e \rightarrow \tau$Y) ~ 10^{-8}

Leptoquarks
- Color triplet particles
- Couple to leptons & quarks
- Mediate CLFV processes at tree-level

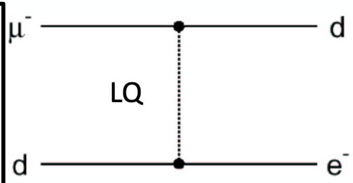
Supersymmetry



Heavy Z



Leptoquarks



BSM models that predict CLFV

Charged Lepton Flavor Violation: **Decay Channel(s)**

1 Prong

$$\tau \rightarrow \mu \nu_{\mu} \nu_{\tau}$$

1. Larger branching ratio ~ 17%
2. Suppression of SM background
3. Needs (good) μ identification

μ channel

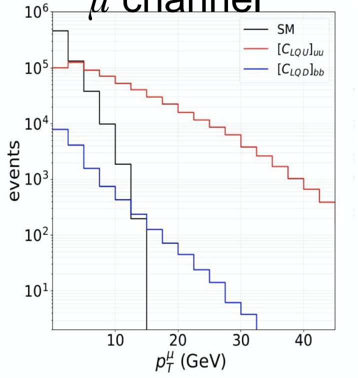


*Image courtesy of Emanuele Mereghetti

[Charged Lepton Flavor Violation at the EIC]

3 Prong (from $e \rightarrow \tau$)

$$\tau \rightarrow \pi^- \pi^+ \pi^- \nu_{\tau}$$

1. Identification is easier than 1 prong channel