SoLID Parity Violating Electron Scattering Program

Michael Nycz

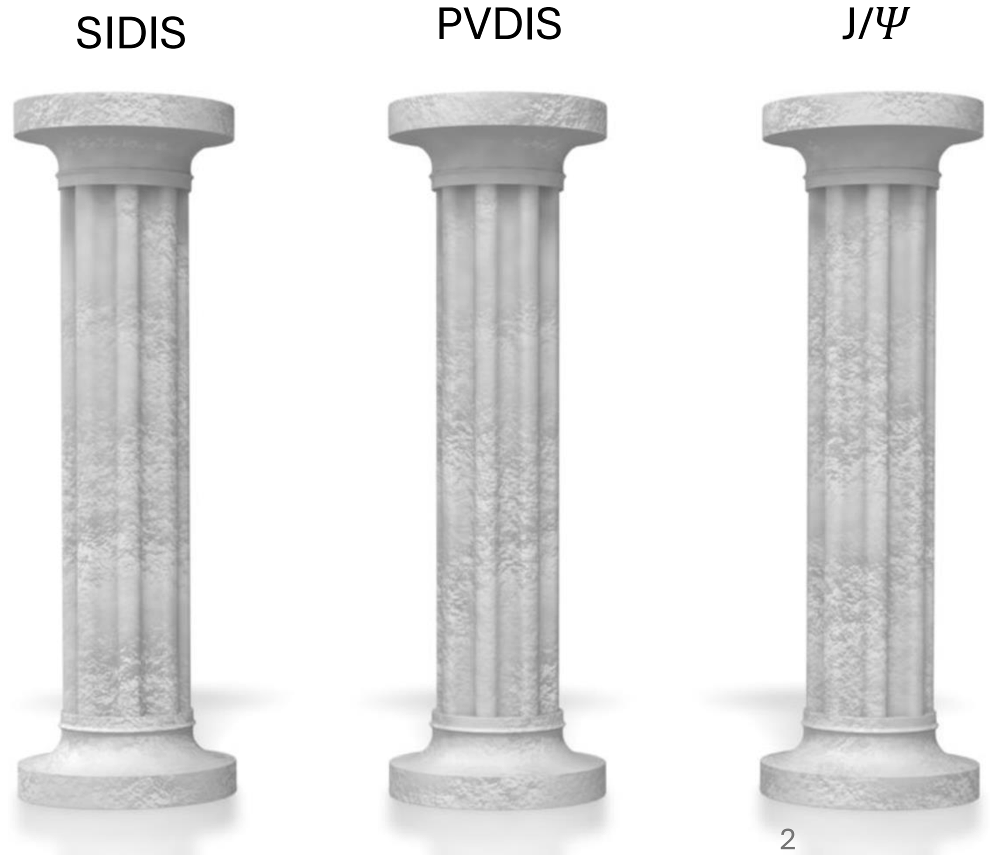
Joint Hall A/C Summer Meeting

June17-18

UNIVERSITY of VIRGINIA

For the SoLID Collaboration

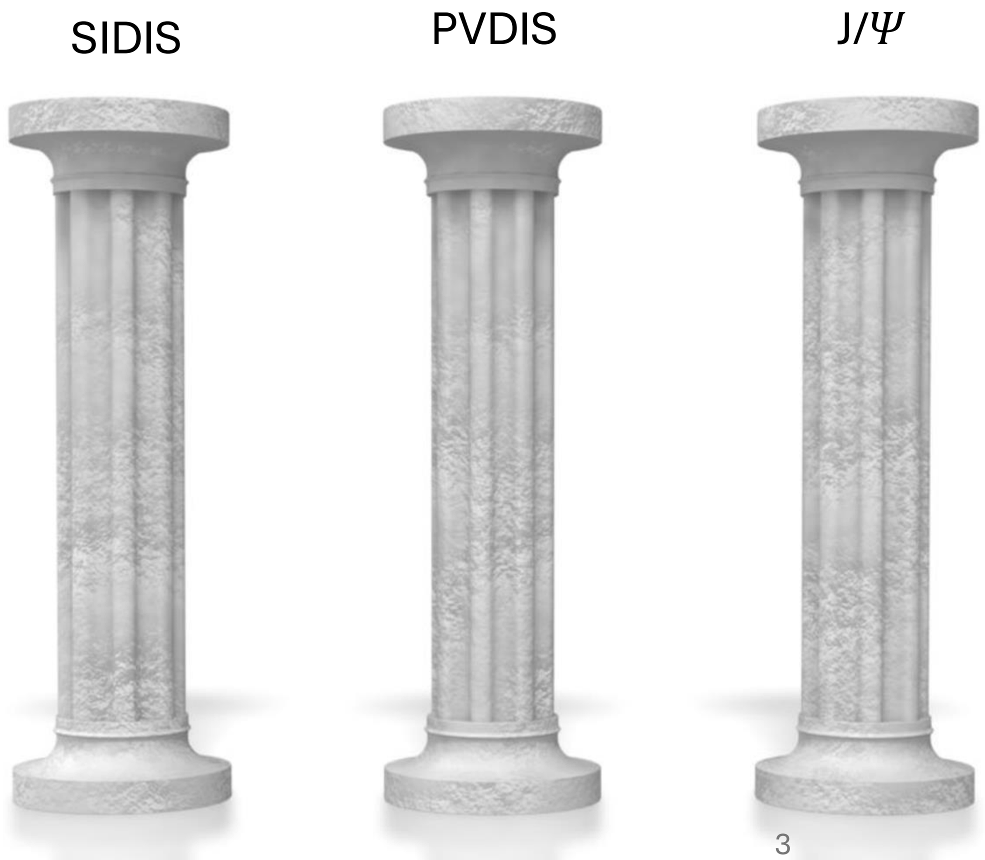
SoLID Experimental Program



SoLID Experimental Program

<u>Established Physics Program</u>

- SIDIS
  - SIDIS with Transversely Polarized ^{3}He(E12-10-006)
  - SIDIS with Longitudinally Polarized ^{3}He(E12-11-007)
  - SIDIS with Transversely Polarized Proton (E12-11-108)
- PVDIS
  - PVDIS (E12-10-007)
- J/Ψ
  - J/Ψ (E12-12-006)
- 6 Approved Run Group Experiments
  - SIDIS Dihadron with Transversely Polarized ^{3}He
  - SIDIS in Kaon Production with Transversely Polarized ^{1}H & ^{3}He
  - Target SSA Measurements in DIS with Transversely Polarized ^{1}H & ^{3}He
  - Measurement of Deep Exclusive π^- Production using a Transversely Polarized ^{3}He
  - TCS with circular polarized beam and unpolarized LH2 target



SoLID Experimental Program

Evolving Physics Program

- SIDIS
  - SIDIS with Transversely Polarized ^3He(E12-10-006): A rating
  - SIDIS with Longitudinally Polarized ^3He(E12-11-007): A rating
  - SIDIS with Transversely Polarized Proton (E12-11-108): A rating
- PVDIS
  - PVDIS (E12-10-007): A rating
  - BNSSA (E12-22-004): A- rating
  - PVEMC (E12-22-002): C2
- J/Ψ
  - J/Ψ (E12-12-006): A rating
- 6 Approved Run Group Experiments
  - SIDIS Dihadron with Transversely Polarized ^1H
  - SIDIS in Kaon Production with Transversely Polarized Proton & ^3He
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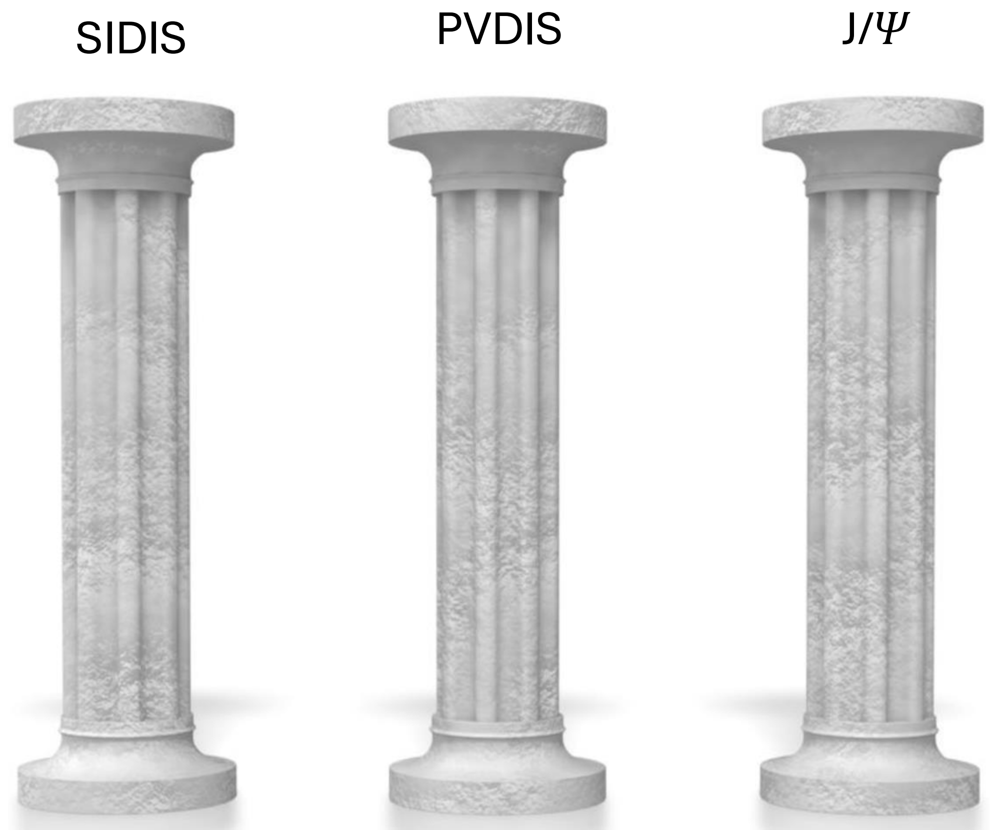

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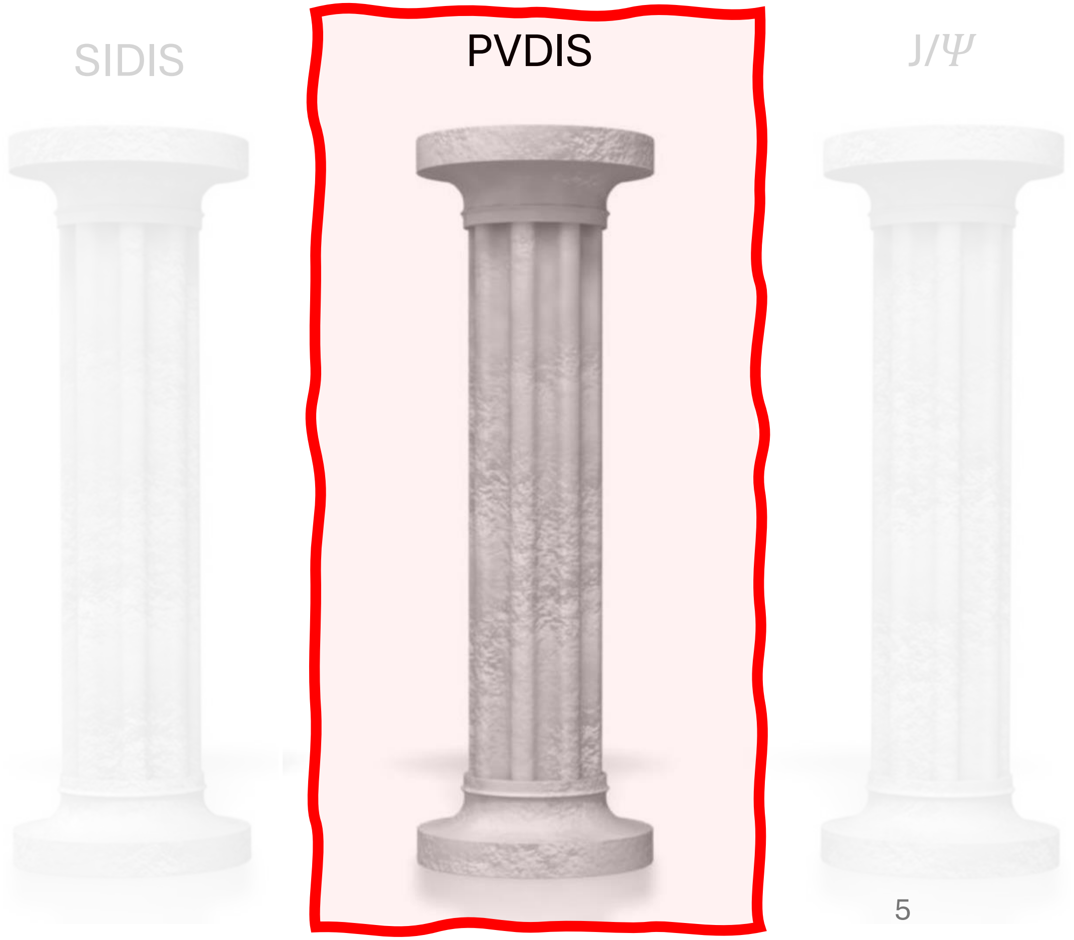
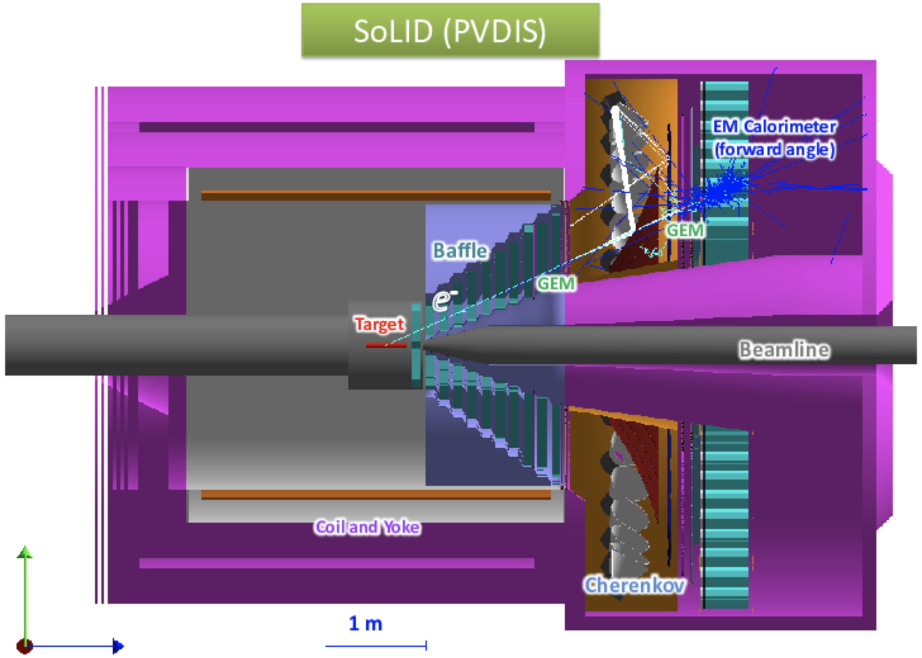


SoLID Parity Violation DIS Program

- **Parity Violating** DIS on Isoscalar Deuteron
  - Precision determination of electroweak parameters
  - Beyond-the-Standard Model (BSM) physics search
  - Search for CSV at quark level
  - Search for quark-quark higher twist effects
- **Parity Violating** DIS on Proton Target
  - Hadronic physics → d/u measurement
- **Parity Violating** EMC Effect
  - Isospin dependence of the EMC effect by the use of neutron-rich isotopes
- Beam-Normal Single Spin Asymmetry using SoLID **PVDIS Configurations**



- High luminosity
  - $L \sim 10^{37} - \mathbf{10^{39}}\ cm^{-2}s^{-1}$
- Large acceptance + full azimuthal coverage

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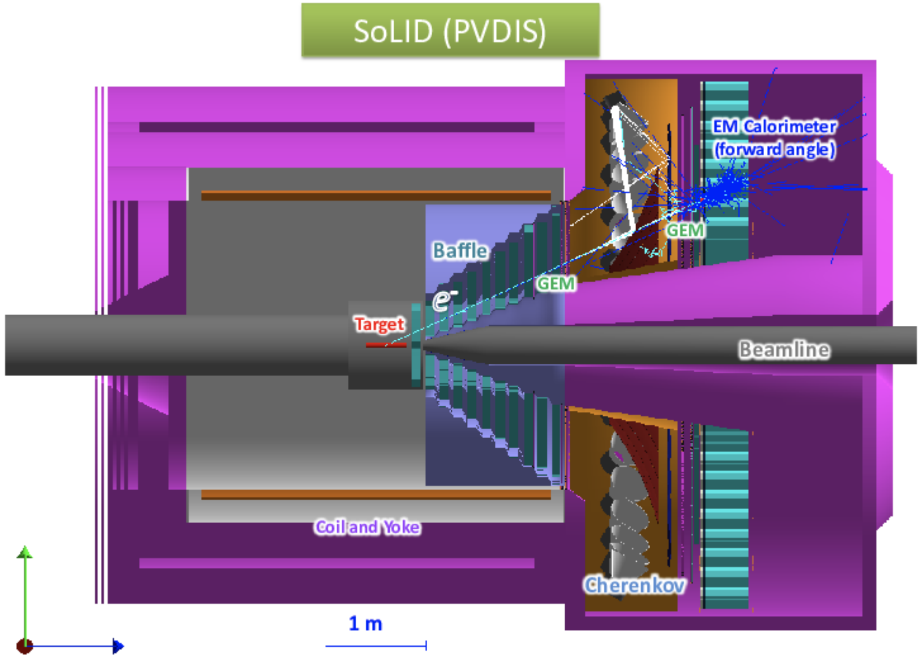


Parity Violation DIS

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

right & left-handed electron

Parity Violation DIS

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

A_{PV} is due to the interference between electromagnetic and weak interaction

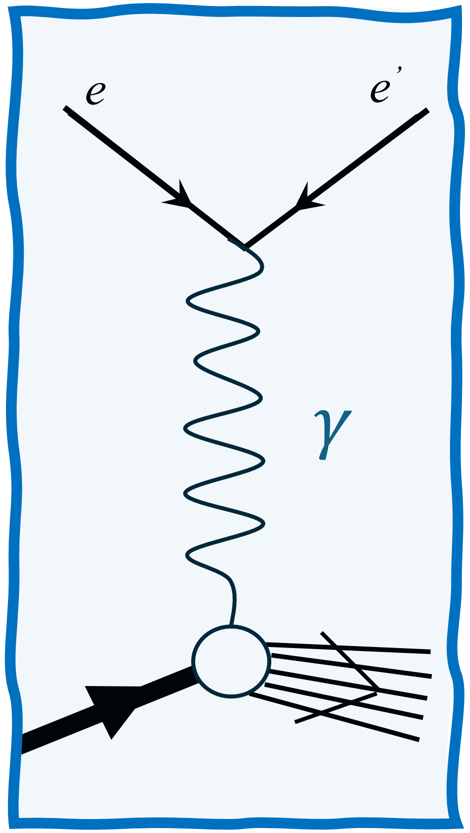
$$\sigma_R \propto \left| M_{EM} + M_Z^R \right|^2$$

$$\sigma_L \propto \left| M_{EM} + M_Z^L \right|^2$$

$$A_{PV} \sim \frac{M_Z^R - M_Z^L}{M_{EM}}$$

EM Interaction

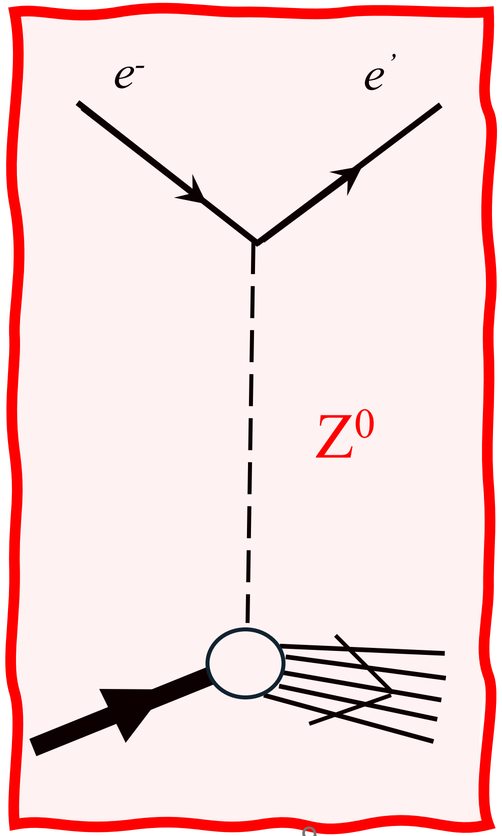
Parity conserving



+

Weak Interaction

Parity violating



Parity Violation DIS

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

In DIS regime, the asymmetry can be expressed as:

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

$$a_1(x) = 2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}}, \quad a_3(x) = g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}}, \; Y = \frac{1-(1-y)^2}{1-(1+y)^2}$$

$$F_1^{\gamma}(x,Q^2) = \frac{1}{2}\sum Q_{q_i}^2 \left[q_i(x,Q^2) + \bar{q}_i(x,Q^2)\right],$$

$$F_1^{\gamma Z}(x,Q^2) = \sum Q_{q_i}\, g_V^i \left[q_i(x,Q^2) + \bar{q}_i(x,Q^2)\right],$$

$$F_3^{\gamma Z}(x,Q^2) = 2\sum Q_{q_i}\, g_A^i \left[q_i(x,Q^2) - \bar{q}_i(x,Q^2)\right]$$

$g_{V,A}^{e,i}$ → vector and axial coupling of the electron or quark of flavor i

PVDIS Isoscalar Deuteron

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For an Isoscalar Deuteron Target, A_{PV} reduces to

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

$A_{PV,(d)}$ at high x

1. **Independent of pdfs**, x W
2. Well-defined SM prediction for Q^2 & y

PVDIS Isoscalar Deuteron

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<u>Low energy electron-quark effective couplings</u>

- $g_{AV}^{eu} = 2g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W$
- $g_{VA}^{eu} = 2g_V^e g_A^u = -\frac{1}{2} - 2\sin^2\theta_W$
- $g_{AV}^{ed} = 2g_A^e g_V^d \approx -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$
- $g_{VA}^{ed} = 2g_V^e g_A^d \approx \frac{1}{2} - 2\sin^2\theta_W$

1. PVDIS Asymmetry is sensitive to both g_{VA}^{eq} and g_{AV}^{eq}
2. PVES (elastic) Asymmetry only sensitive to g_{AV}^{eq}

SoLID PVDIS: Deuteron

Title: Precision Measurement of Parity-Violation in Deep Inelastic Scattering over a Broad Kinematic Range

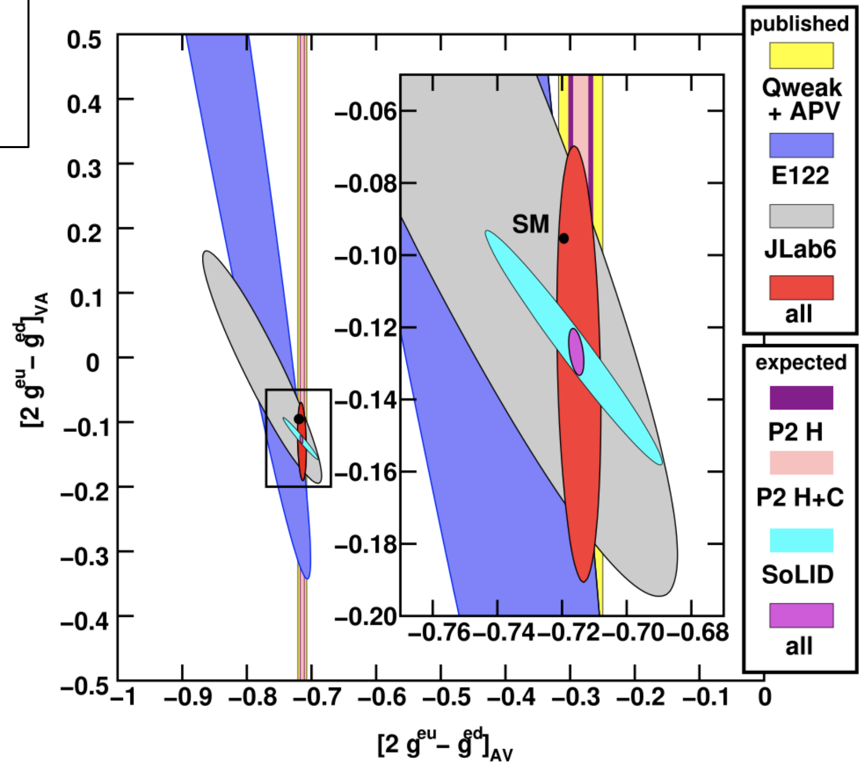
Spokespersons: P. Souder (contact), X. Zheng, P. E. Reimer

- Dominant uncertainties: experimental systematics

Polarimetry	**0.4**
Q^2	**0.2**
Radiative Corrections	**0.2**
Event Reconstruction	**0.2**

- **Able to measure Apv to sub–percent level precision**

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



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

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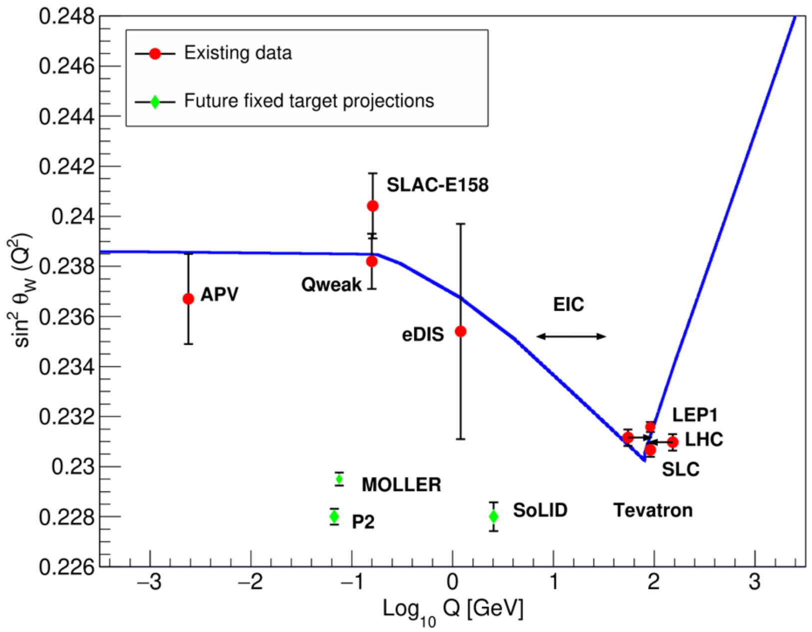
$\longrightarrow \sin^2\theta_w(Q^2)$



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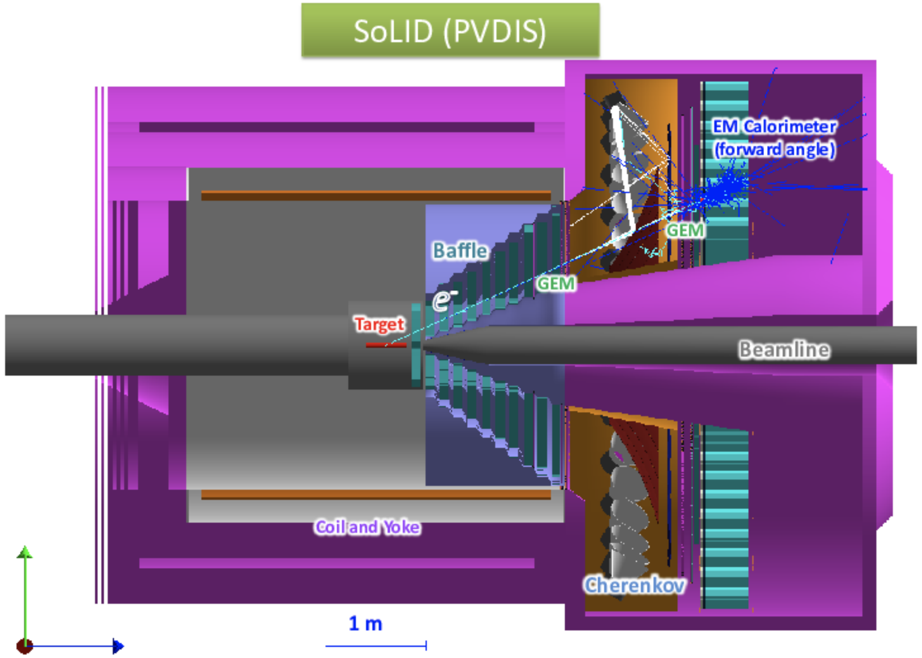
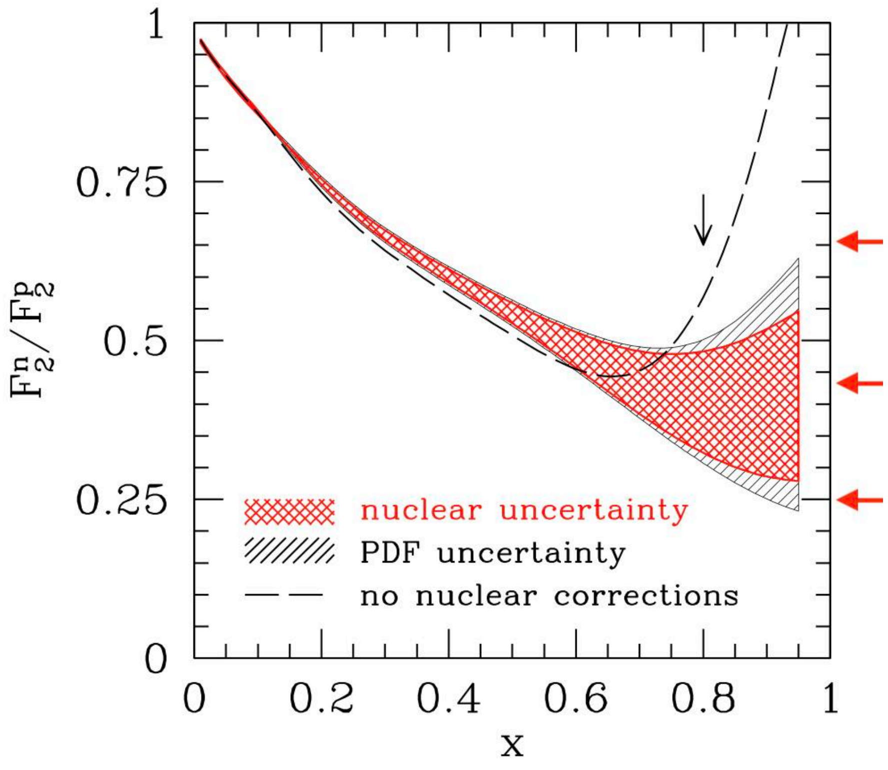


SoLID PVDIS Program: Proton

- Ratios F_2^n/F_2^p & d/u ($\lim x \longrightarrow 1$)
  - Provide clear way to examine theory
- Major hurdle
  - Extracting F_2^n
- $F_2^p \longrightarrow$ Hydrogen
- $F_2^n \longrightarrow$? (No free / stable neutron target)



	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Diquark Model/Feynman	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
Quark Counting Rules	3/7	1/5	1	1

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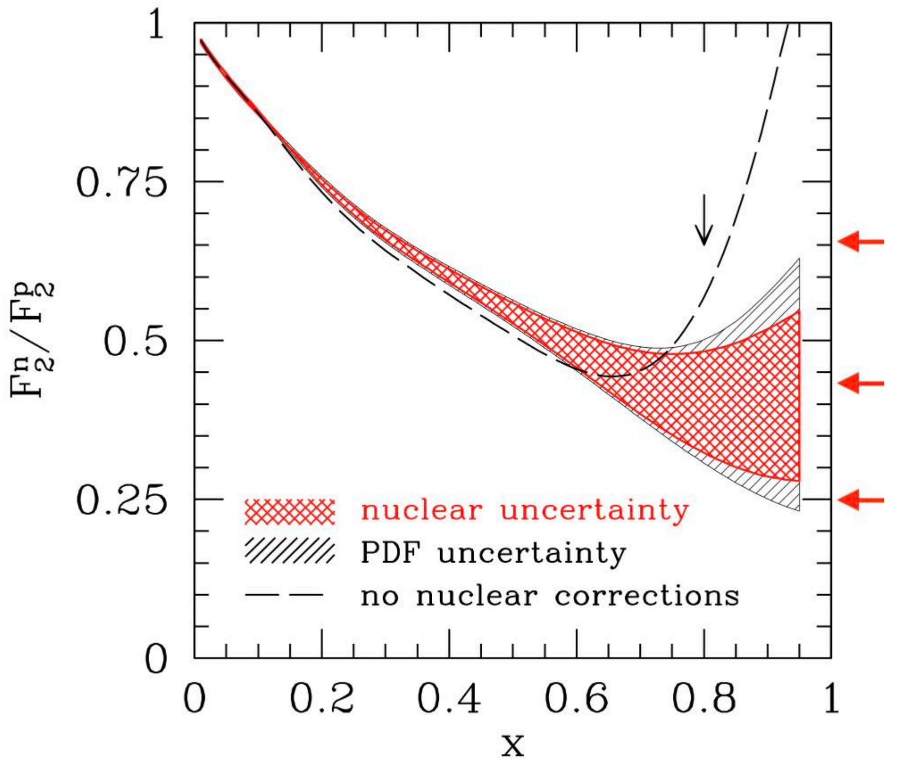
- $F_2^D = F_2^n + F_2^p$

Extract

Measure



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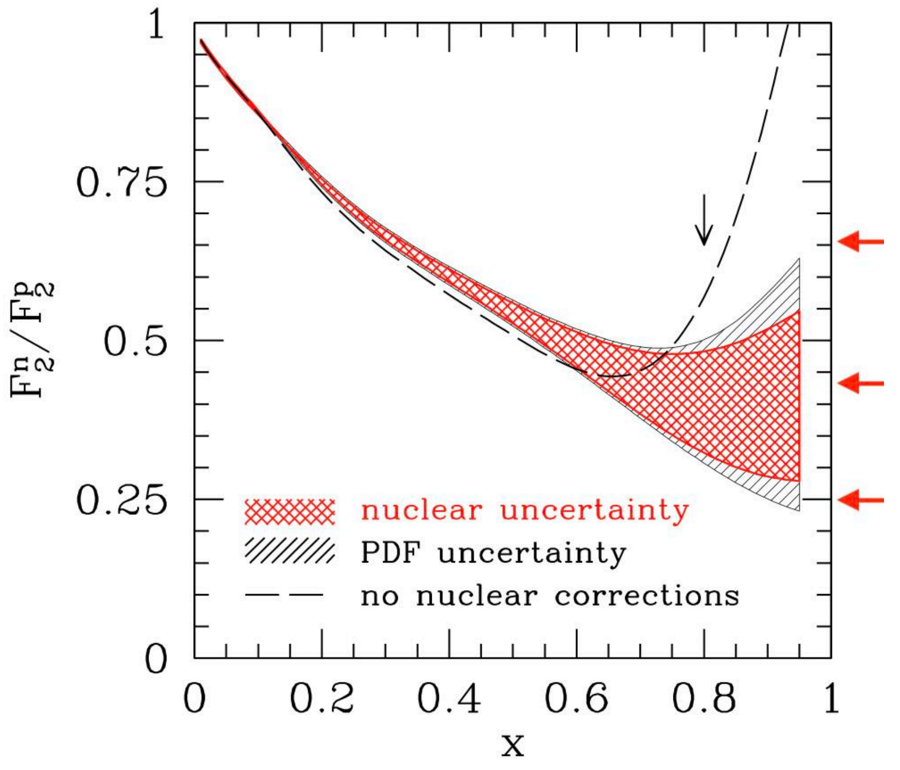
Extract

Measure

Not so straight forward



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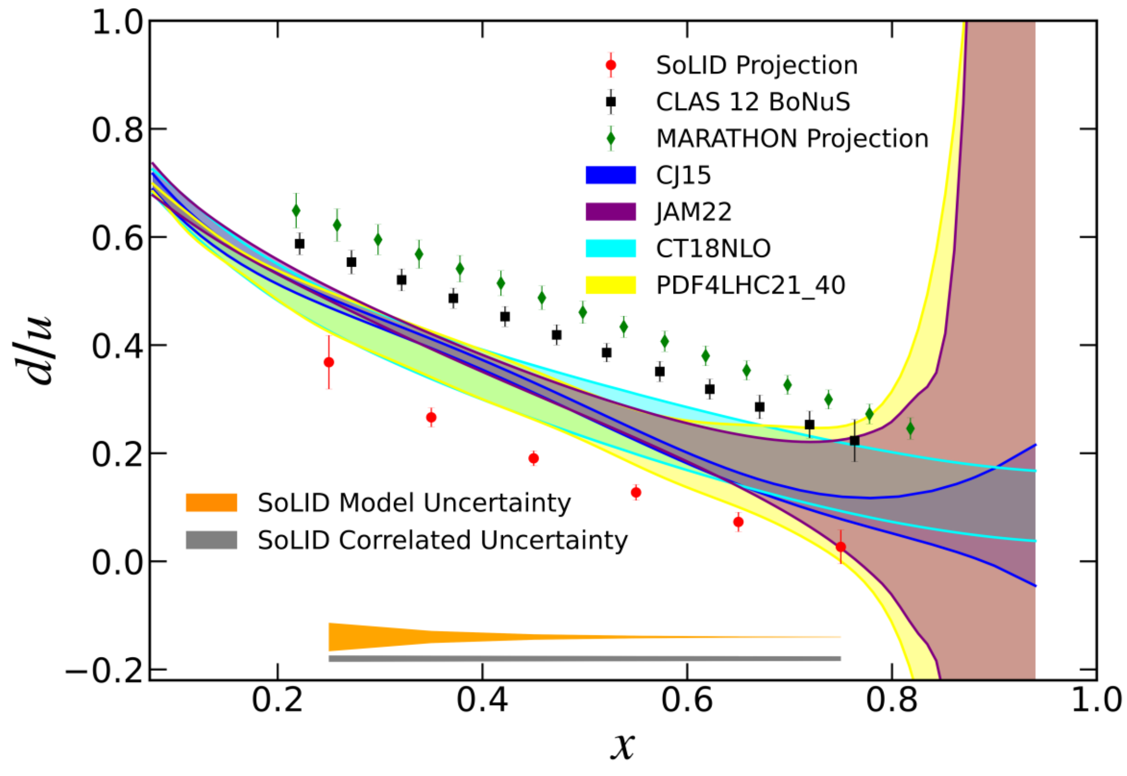
SoLID PVDIS Program: Proton

d/u measurement

- BoNuS (Barely Off-Shell Neutron Structure)
  - Tag recoiling (low momentum) proton
- MARATHON (Ratio of A=3 mirror nuclei)
  - Nuclear effects cancel in ratio: $\frac{^3\mathrm{H}}{^3\mathrm{He}}$
- SoLID PVDIS on ^{1}H
- d/u **obtained free of nuclear effects**

$$A_{PV} = \frac{Q^2}{4\pi\alpha v^2} \frac{\left[12g_{AV}^{eu} - 6g_{AV}^{ed}\frac{d}{u}\right]}{4 + \frac{d}{u}}$$



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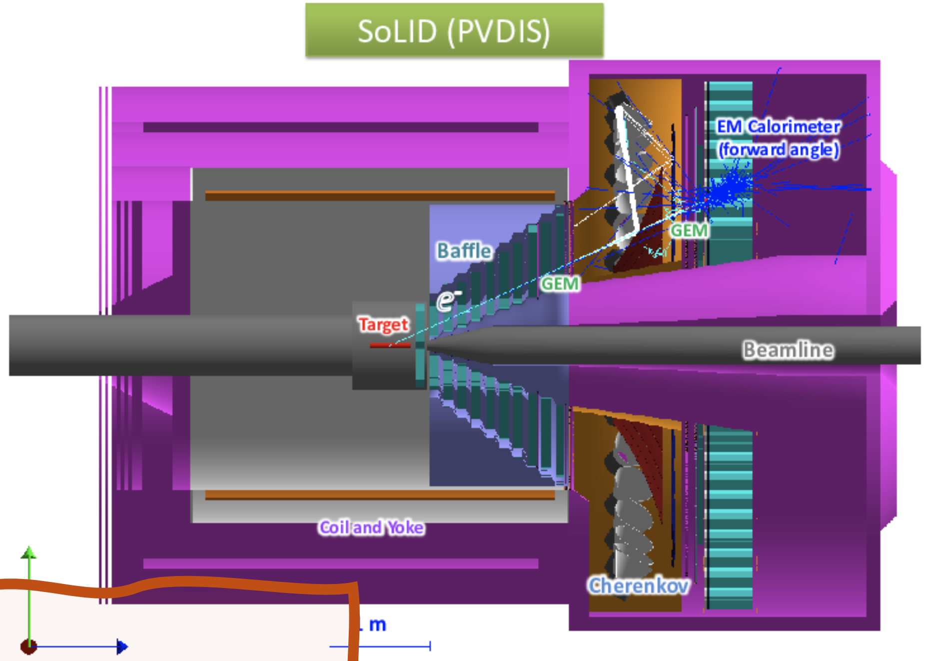
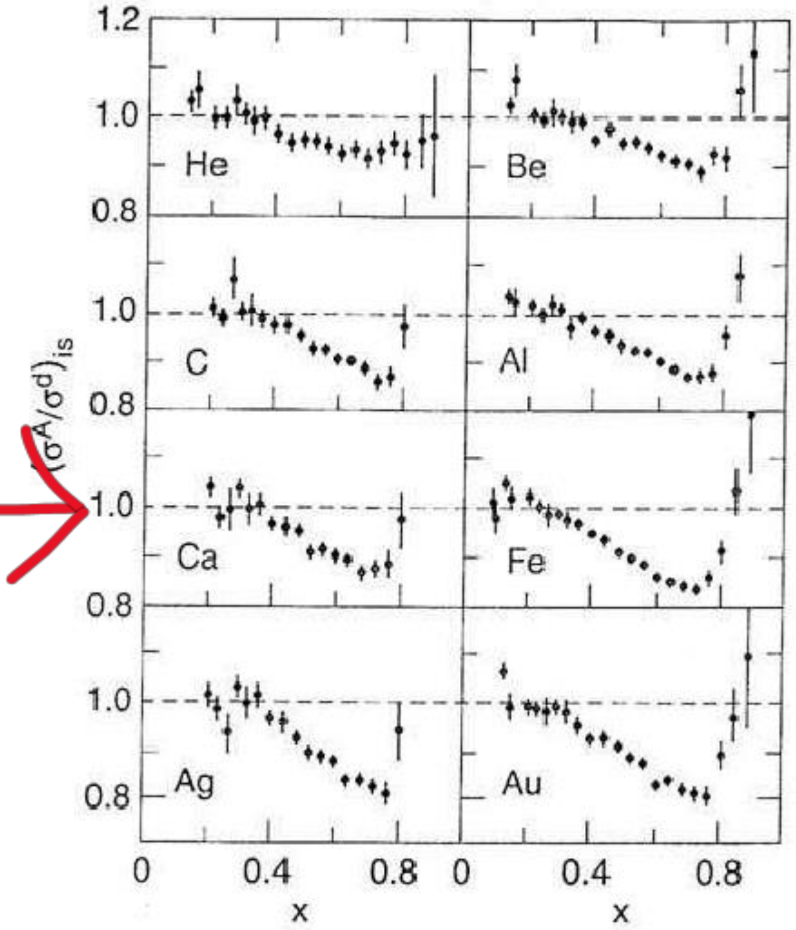


EMC Effect

$$F_2^D \neq F_2^n + F_2^p$$

- **E**uropean **M**uon **C**ollaboration: F_2^{Fe}/F_2^D
  - Expected the ratio to be ~ unity (x < 0.7)
  - Modification of quark distributions
- Universal x behavior
  - SLAC E139



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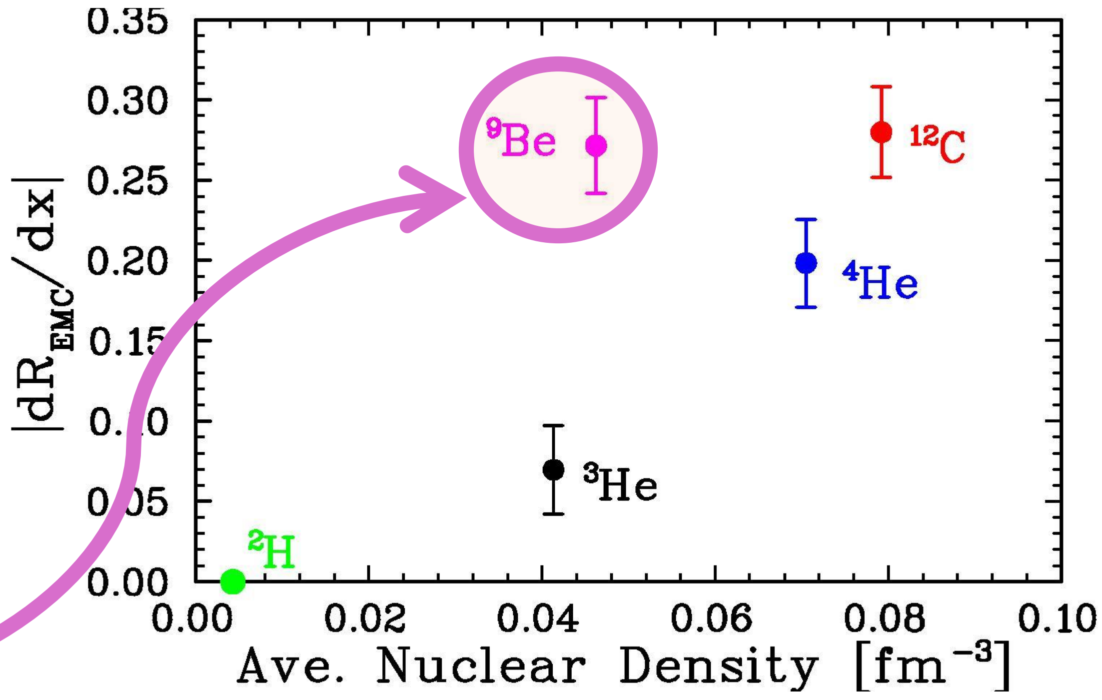
- Size does NOT scale with density
  - ^{9}Be is low density
  - ‘large’ EMC effect
- Definitive explanation.....
  - Competing explanations



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  - 'large' EMC effect
- Definitive explanation.....
  - Competing explanations
- Need new observables

Flavor Dependent EMC

1. EMC-SRC correlation + n-p dominance of SRCs
   a. enhanced EMC effect in minority nucleons
2. Neutron rich nuclei like ^{48}Ca
   a. expected to have significant neutron skin
   b. neutrons preferentially sit near the surface in lower density regions
3. Calculations show difference for u-, d-quark
   a. scalar and vector mean-field potentials in asymmetric nuclear matter

Indicate enhanced EMC for minority nucleons

Parity Violation EMC Effect

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

Suppressed

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

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

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

Target Choice

- ❑PVEMC target requirement
  - ❑Target with N ≠ Z
  - ❑Large EMC effect

} ^{48}Ca

PVDIS sensitive to difference in up and down quark distributions in nuclei

Parity Violation EMC Effect

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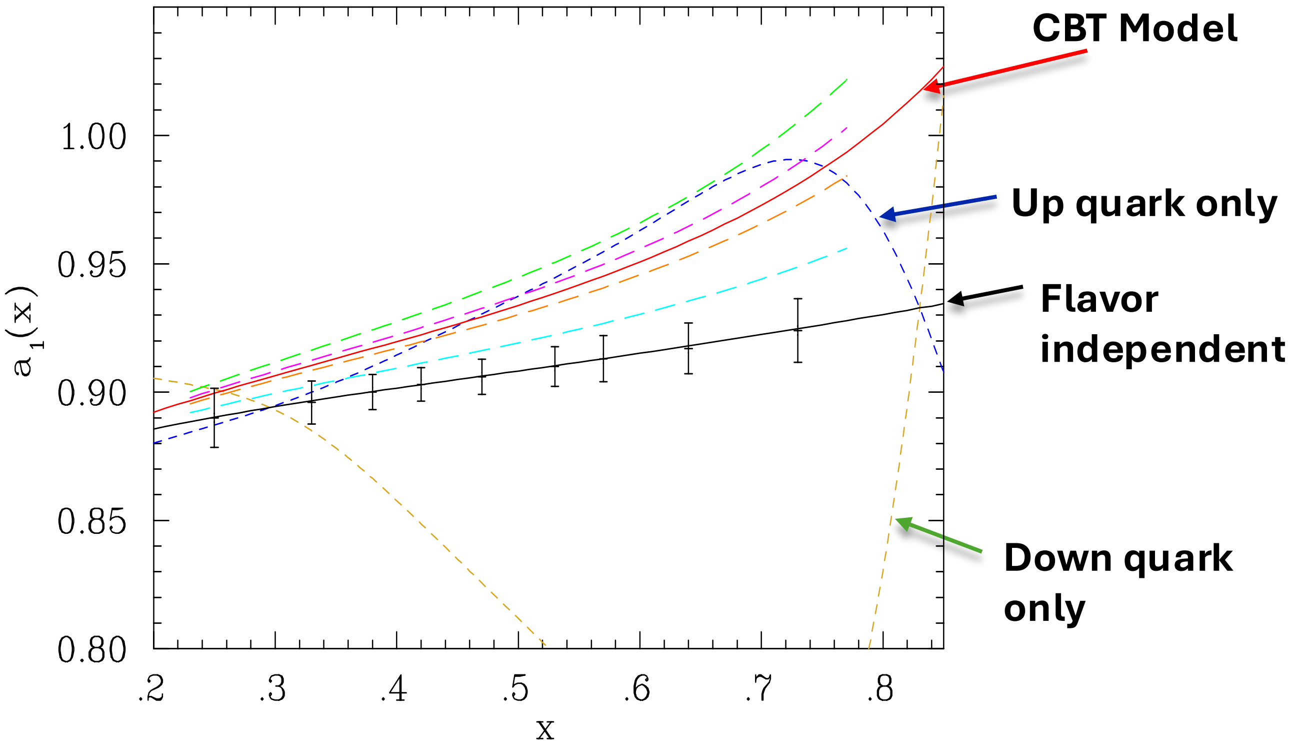
Title: First Measurement of the Flavor Dependence of Nuclear PDF Modification Using Parity-Violating Deep Inelastic Scattering

Spokespersons: J. Arrington (contact), R. Beminiwattha, D. Gaskell, J. Mammei, P. Reimer



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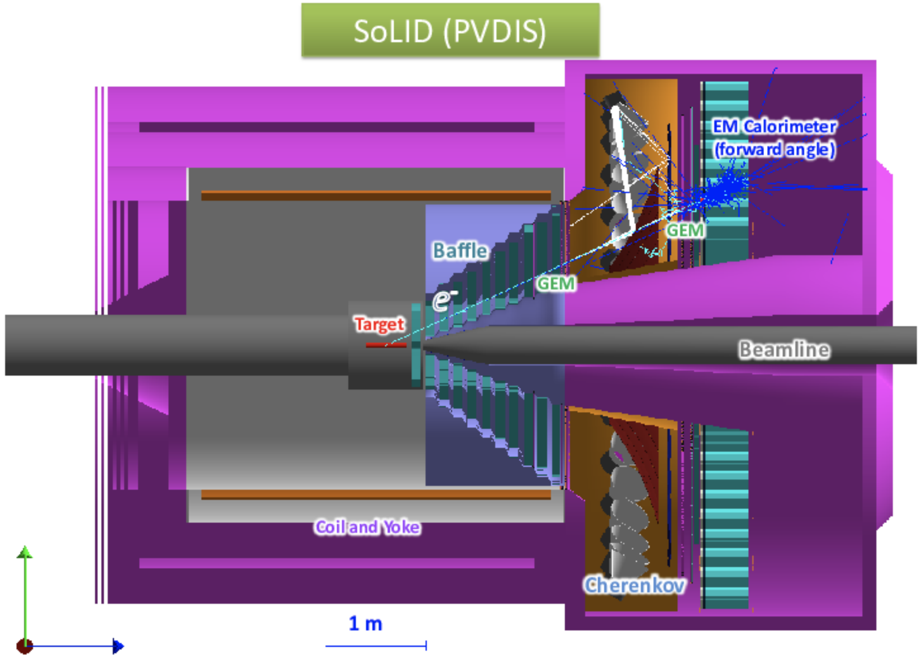
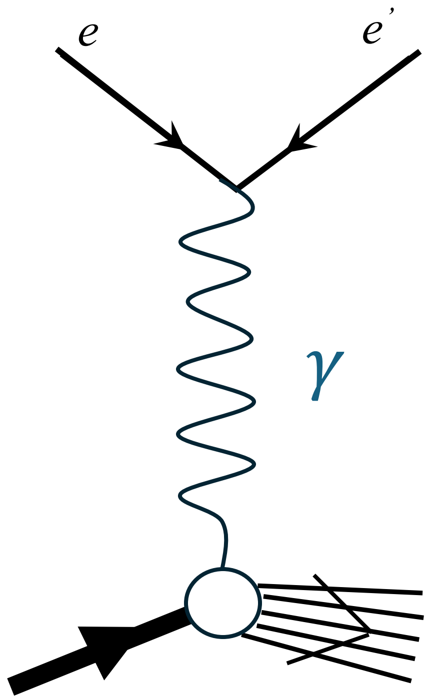


Beam-Normal Single Spin Asymmetry

- **Transversely** polarized lepton beam or target
  - Born approximation (OPE)
  - Asymmetry is zero (time reversal invariance & parity)

$$\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}$$



PHYSICAL REVIEW VOLUME 143, NUMBER 4 MARCH 1966

Possible Tests of C_{st} and T_{st} Invariances in $l^{\pm}+N \rightarrow l^{\pm}+\Gamma$ and $A \rightarrow B+e^{+}+e^{-}$†

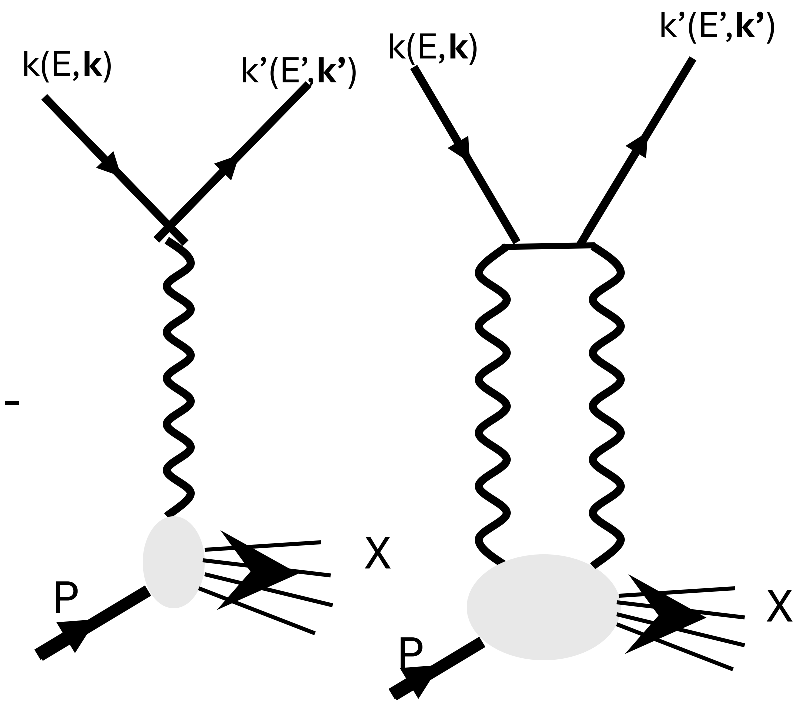
N. CHRIST* AND T. D. LEE
Department of Physics, Columbia University, New York, New York

(Received 8 November 1965)

A systematic method to test the C_{st} and T_{st} invariances of the electromagnetic interaction is to use the inelastic scattering $l^{\pm}+N \rightarrow l^{\pm}+\Gamma$ where $l^{\pm}$ is the charged lepton, N is the target nucleus (or nucleon), and $\Gamma \neq N$ but, otherwise, can be any system of the strongly interacting particles. General expressions for the various possible C_{st}- and T_{st}-noninvariant effects in such reactions are derived and discussed. Similar considerations are also applied to the decay $A \rightarrow B+e^{+}+e^{-}$, where A and B are any complexes of the strongly interacting particles.

Beam-Normal Single Spin Asymmetry

- **Transversely** polarized lepton beam or target
  - Born approximation (OPE)
  - Asymmetry is zero (time reversal invariance & parity)
- Beyond Born approximation
  - Non-zero asymmetry generated by interference between single- and two-photon exchange processes
- Beam-Normal SSA probes Imaginary part of TPE
  - $A_n \propto \boldsymbol{Im}\, T_{1\gamma} T_{2\gamma}^*$



Beam-Normal Single Spin Asymmetry: E12-22-004

- **Transversely** polarized lepton beam or target
  - Born approximation (OPE)
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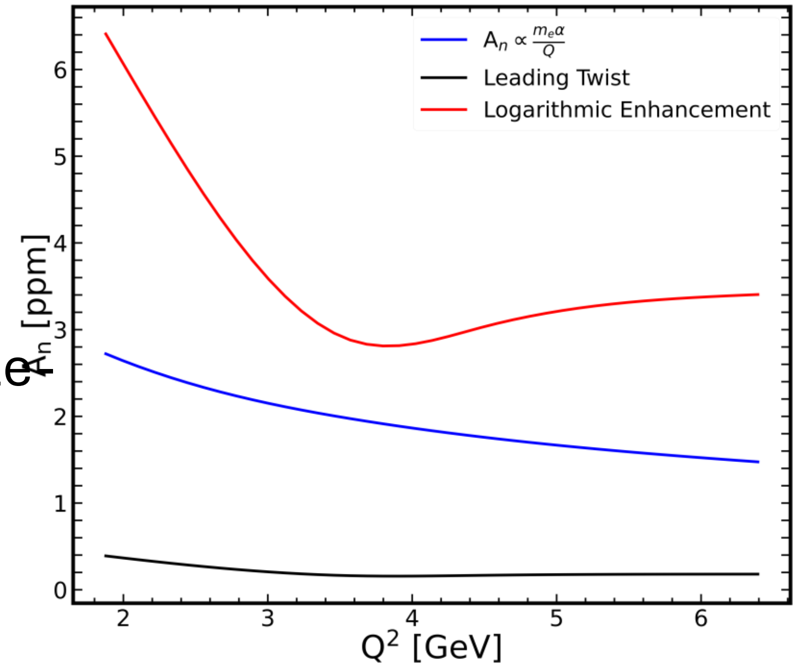
- Beyond Born approximation
  - Non-zero asymmetry generated by interference between single and two-photon exchange processes
- Beam-Normal SSA probes Imaginary part of TPE
  - $A_n \propto \boldsymbol{Im}\, T_{1\gamma} T_{2\gamma}^{*}$
- Beam Normal SSA proportional to the m_e
- Small asymmetry
  - High Luminosity→ SoLID



Beam-Normal Single Spin Asymmetry: E12-22-004

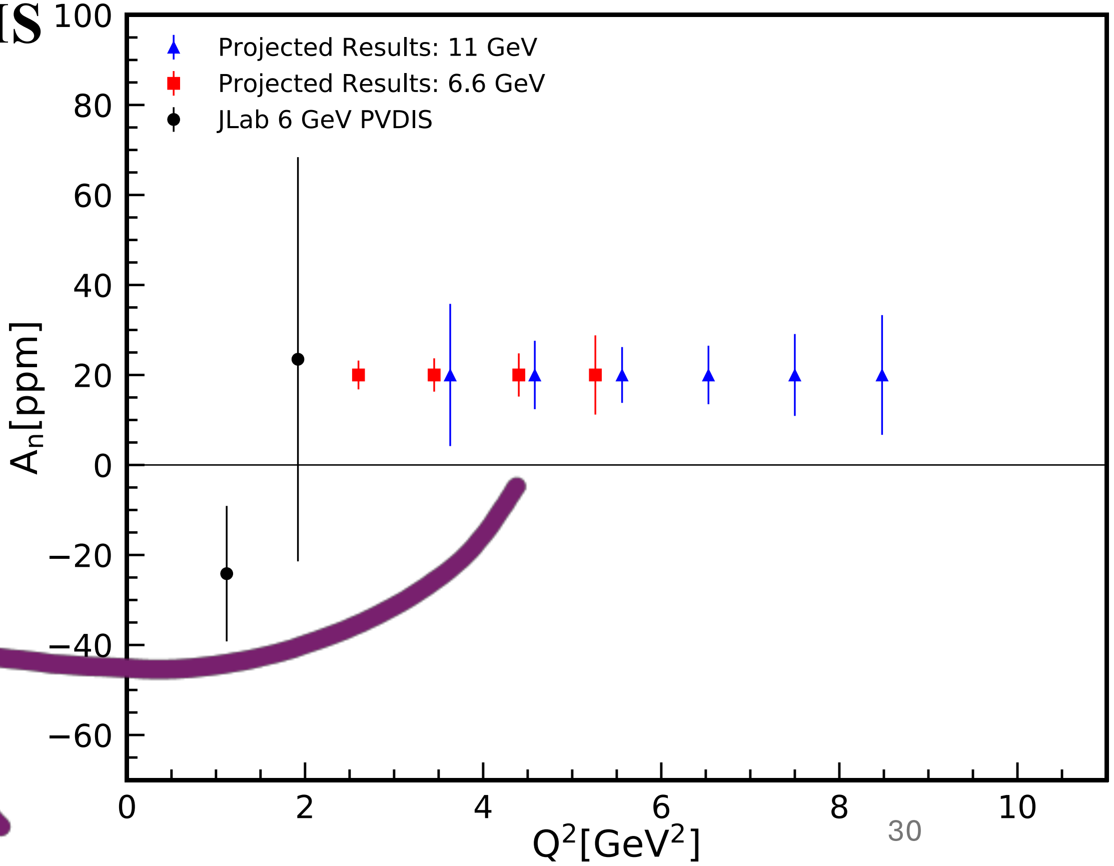
Title: Measurement of the Beam Normal Single Spin Asymmetry in Deep Inelastic Scattering using the SOLID Detector

Spokespersons: M. Nycz (contact), X. Zheng, W. Henry, Y. Tian, W. Xiong

First high precision Beam-normal SSA measurement in DIS

1. Non-zero BNSSA in DIS?
2. Dominant mechanism?
   a. Synergy with SoLID target normal SSA
3. Important input for theoretical models
4. TPE in DIS (SIDIS)?

Can combine Q^2 bins in each energy setting



Beam-Normal Single Spin Asymmetry: E12-22-004

Title: Measurement of the Beam Normal Single Spin Asymmetry in Deep Inelastic Scattering using the SOLID Detector

Spokespersons: M. Nycz (contact), X. Zheng, W. Henry, Y. Tian, W. Xiong

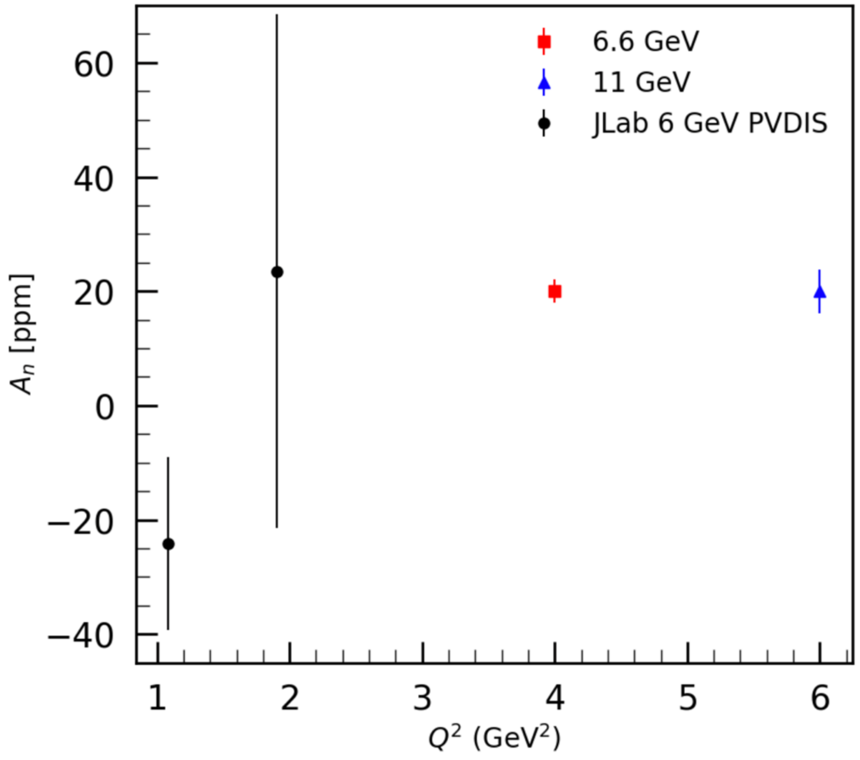
First high precision Beam-normal SSA measurement in DIS

1. Non-zero BNSSA in DIS?
2. Dominant mechanism?
   a. Synergy with SoLID target normal SSA
3. Important input for theoretical models
4. TPE in DIS (SIDIS)?

Can combine Q^2 bins in each energy setting

$A_n = A_{measured} \pm 2.06$ ppm : 6.6 GeV

$A_n = A_{measured} \pm 3.80$ ppm : 11 GeV



Beam-Normal Single Spin Asymmetry: E12-22-004

- Beam Normal SSA in Standard Model Effective Field Theory (SMEFT)

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Transverse spin asymmetries at the EIC as a probe of anomalous electric and magnetic dipole moments

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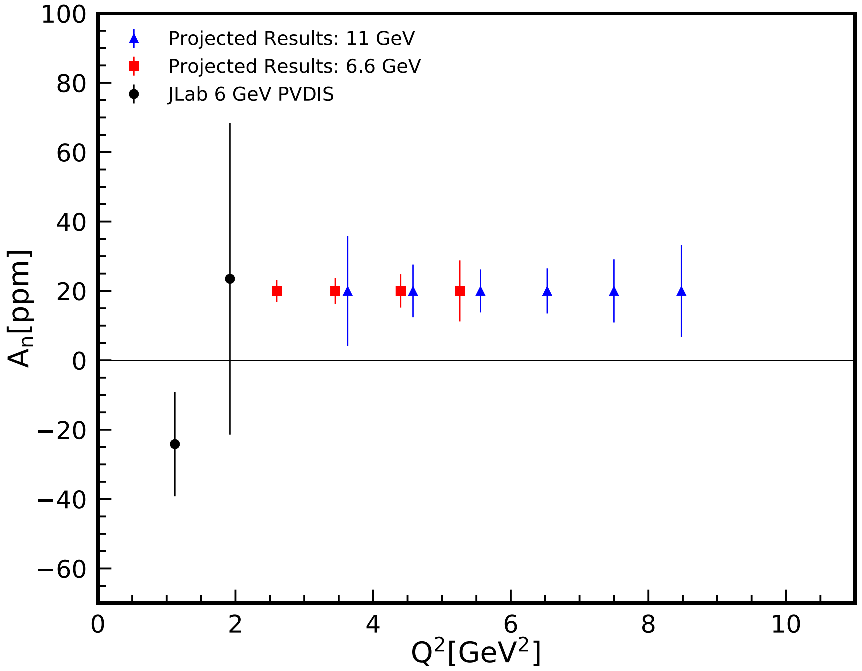
- An effective field theory extension of the SM
  - includes terms suppressed by a high energy scale Λ

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \ldots$$

Beam-Normal Single Spin Asymmetry: E12-22-004

- Beam Normal SSA in Standard Model Effective Field Theory (SMEFT)
- Ongoing study to explore the impact of SoLID BNSSA data
  - Precision data from SoLID appears very promising
  - Impact study / publication in near future



Strong Parity Violation in DIS

- Standard Model
  - QCD is invariant under parity transformations (L⟷R)
- Parity invariance of the strong interaction
  - No 1st principle guaranteeing parity invariance for strong interaction

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- Implication of parity violation in strong interactions?
- How to explore potential strong parity violation?

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- Parity invariance of the strong interaction
  - No 1st principle guaranteeing parity invariance for strong interaction
- Implication of parity violation in strong interactions?
- How to explore potential

Signals of strong parity violation in deep inelastic scattering

Alessandro Bacchetta [a,b,*], Matteo Cerutti [a,b], Ludovico Manna [a,c], Marco Radici [b], Xiaochao Zheng [d]

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Structure (Formalism): Neutral-Current DIS

$$\frac{d^2\sigma}{dx_B} = \frac{2\pi\alpha^2}{x_B y Q^2}\left[\left(Y_+ + \frac{R^2 y^2}{2}\right)\left(F_{2,UU} + \lambda F_{2,LU}\right) - y^2\left(F_{L,UU} + \lambda F_{L,LU}\right) - Y_-\left(x_B F_{3,UU} + \lambda x_B F_{3,LU}\right)\right]$$

$$F_{2,UU}(x_B, Q^2) = F_2^{(\gamma)} - g_V^e \eta_{\gamma Z} F_2^{(\gamma Z)} + \left({g_V^e}^2 + {g_A^e}^2\right)\eta_Z F_2^{(Z)}$$

$$F_{2,LU}(x_B, Q^2) = g_A^e \eta_{\gamma Z} F_2^{(\gamma Z)} - 2 g_V^e g_A^e \eta_Z F_2^{(Z)}$$

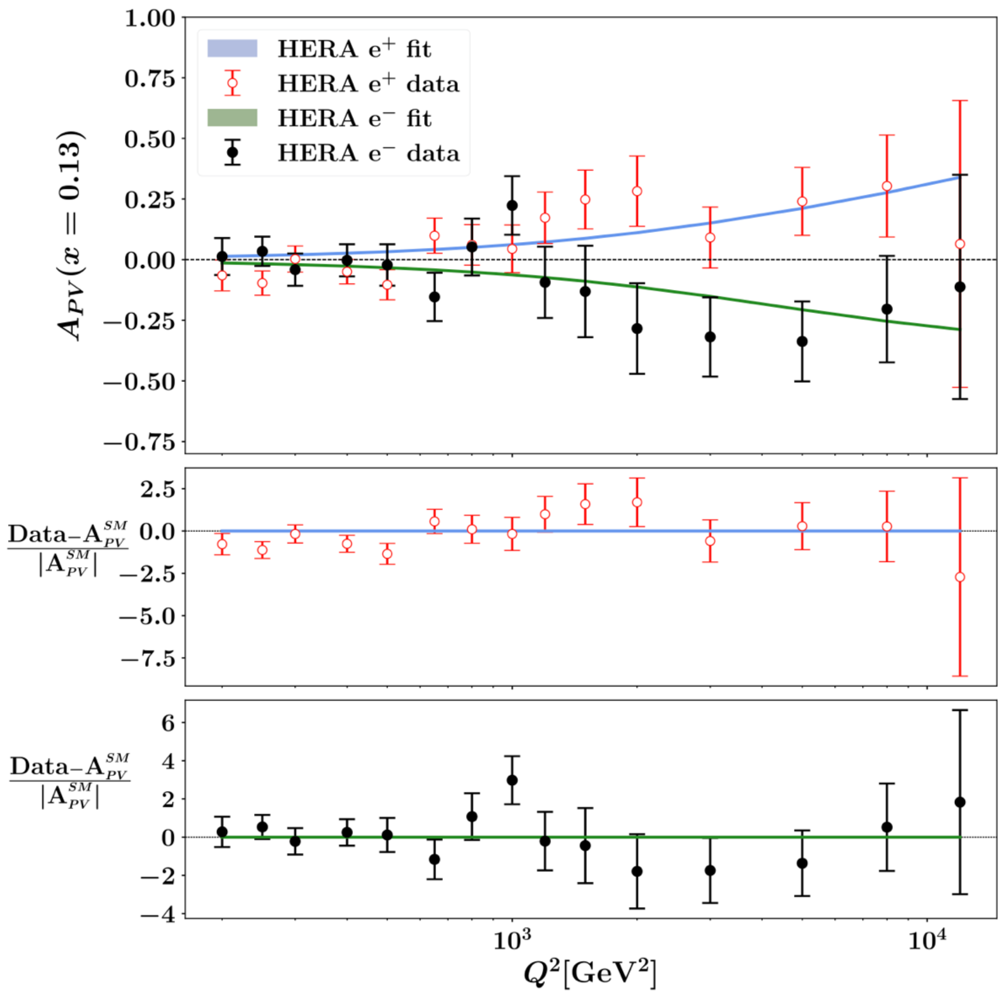
$$F_{3,UU}(x_B, Q^2) = g_A^e \eta_{\gamma Z} F_3^{(\gamma Z)} - 2 g_V^e g_A^e \eta_Z F_3^{(Z)}$$

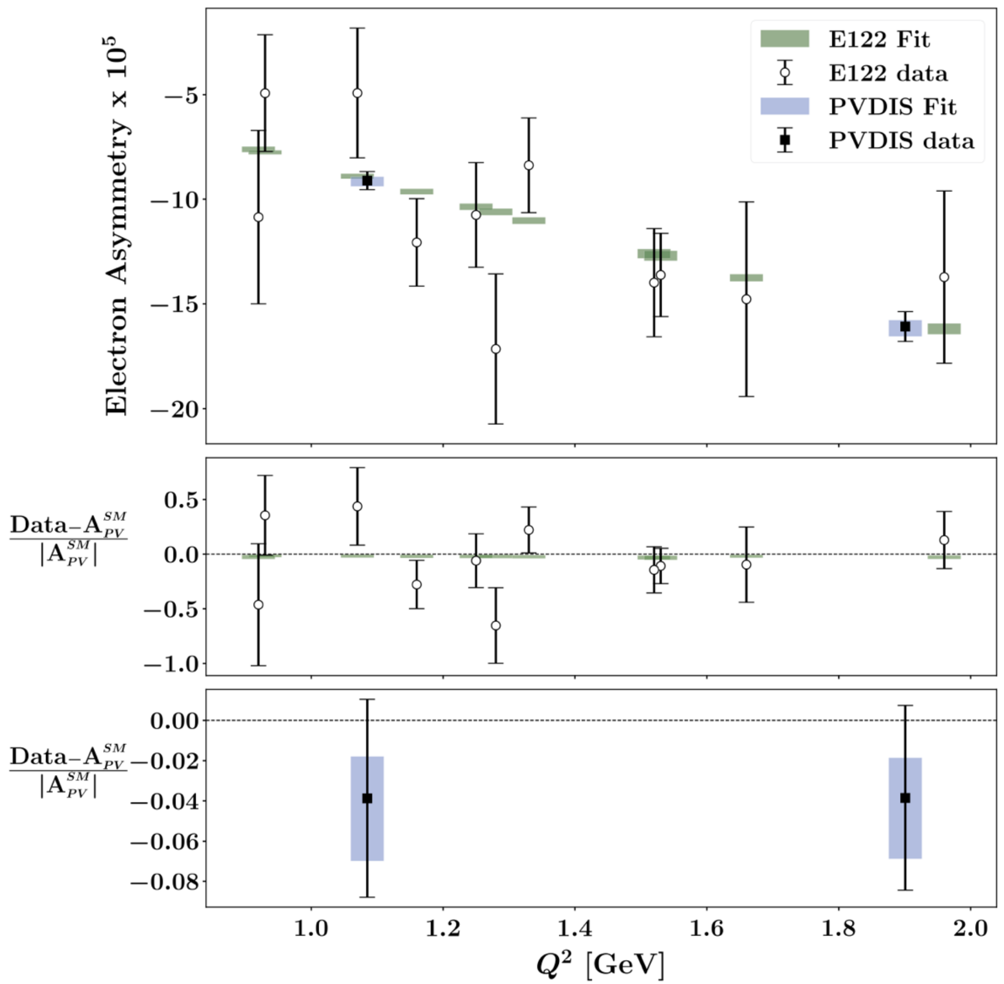
$$F_{3,LU}(x_B, Q^2) = F_3^{(\gamma)} - g_V^e \eta_{\gamma Z} F_3^{(\gamma Z)} + \left({g_V^e}^2 + {g_A^e}^2\right)\eta_Z F_3^{(Z)}$$

SM: No contribution from $F_3^{(\gamma)}$

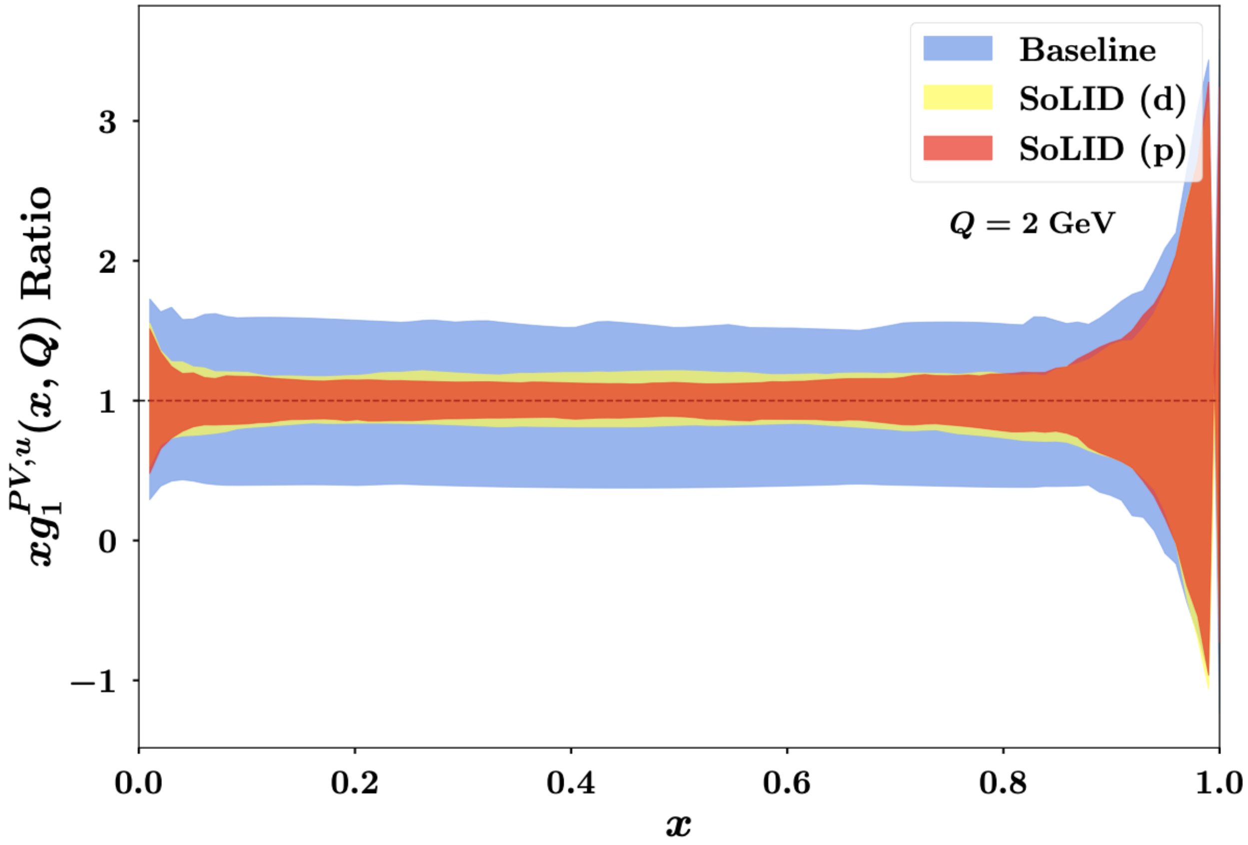
Adds the observable → $F_3^{(\gamma)}$

Strong Parity Violation in DIS: Apply to Existing Data





Strong Parity Violation in DIS



SoLID PVIDS program will make the largest impact

Summary and Outlook

- SoLID has a well established and growing physics program
- SoLID PVDIS has a broad physics program
  - Precision measurements of electroweak parameters
  - d/u free of nuclear effects
  - Flavor dependent EMC effect
  - Two-photon Exchange in DIS
- Potential impacts are being explored
  - Beam-Normal SSA in Standard Model Effective Field Theory
  - Strong parity

Thank You

Beam-Normal Single Spin Asymmetry: E12-22-004

Systematic	Uncertainty
Target endcaps	5%
Polarimetry	3%
Radiative Corrections	1-2%
Particle background	1%
Q^2 determination	0.2%

PVDIS Program