

SoLID PVDIS on deuteron

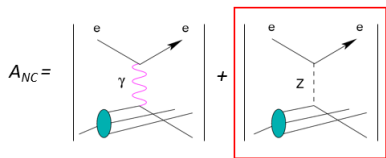
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Neutral-Current Weak Interaction in Electron Scattering

PVES: measure parity violation via asymmetry (A_{PV}) between left- and right-handed e^- beam scattering off unpolarized target



$$J^{NC}(l) = (\bar{u}_l \left[\frac{1}{2}(c_V^l - c_A^l \gamma_5) \right] u_l) \\ i \frac{g}{q^2} \frac{q_\mu q_\nu}{M_Z^2}$$

$$J^{NC}(q) = (\bar{u}_q \left[\frac{1}{2}(c_V^q - c_A^q \gamma_5) \right] u_q)$$

For $Q^2 \ll M_Z^2$:

$$L_{NC}^{lq} = \frac{G_F}{2} \sum_q [C_{0q} \bar{l} \gamma_\mu q + C_{1q} \bar{l} \gamma_\mu q + C_{2q} \bar{l} \gamma_\mu q + C_{3q} \bar{l} \gamma_\mu q]$$

VV

VA, AV (parity-violating)

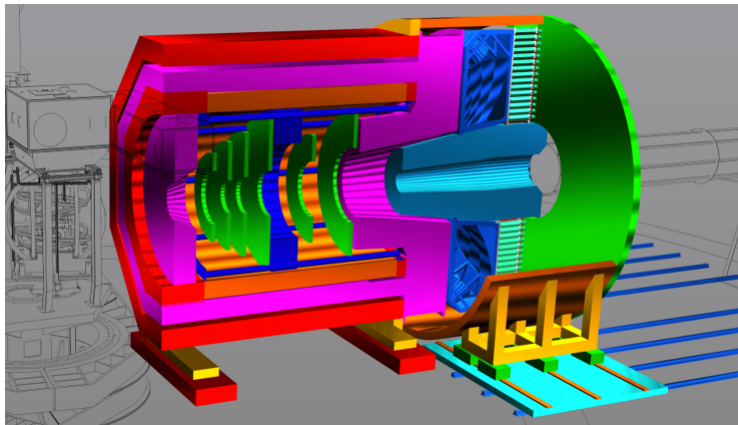
AA

$$C_{1u} = 2g_A^e g_V^u = \frac{1}{2} + \frac{4}{3} \sin^2 \theta_w \quad C_{2u} = 2g_V^e g_A^u = \frac{1}{2} + 2 \sin^2 \theta_w \quad C_{3u} = 2g_A^e g_A^u = \frac{1}{2}$$

$$C_{1d} = 2g_A^e g_V^d = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_w \quad C_{2d} = 2g_V^e g_A^d = \frac{1}{2} - 2 \sin^2 \theta_w \quad C_{3d} = 2g_A^e g_A^d = \frac{1}{2}$$

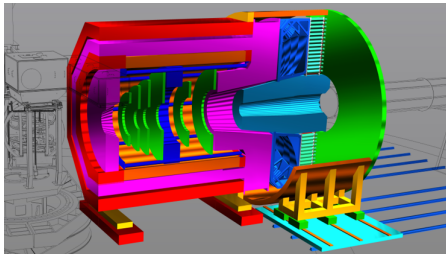
Coherent PVDIS Program with SoLID

Solenoid Large-Intensity Device (SoLID) spectrometer



Coherent PVDIS Program with SoLID

SoLID spectrometer



General purpose device,
several physics topics:

- PVDIS
- SIDIS
- J/Psi production
- DVCS
- ...and more

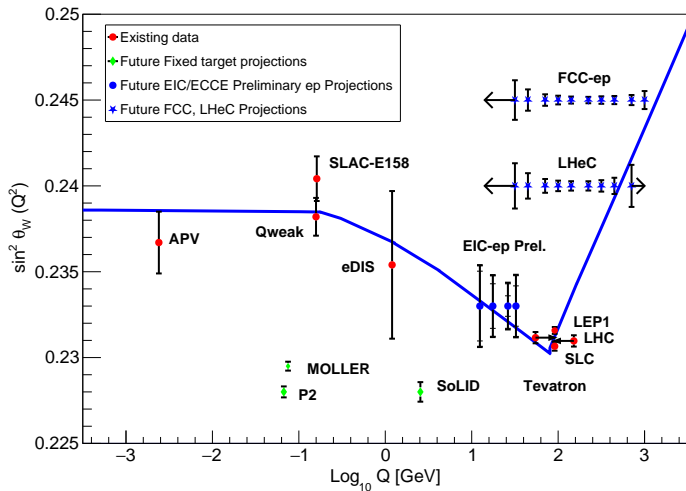
- PVDIS on deuteron:

$$A_{PV} = \frac{G_F Q^2}{4 \frac{\beta}{2}} [a_1 Y_1 + a_3 Y_3]$$

- In the valence quark region ($x > 0.4$):

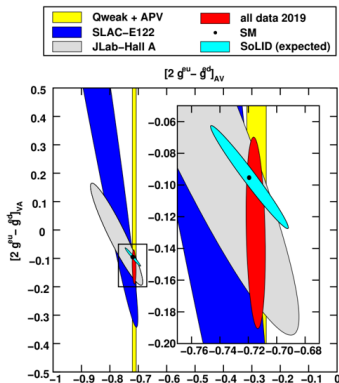
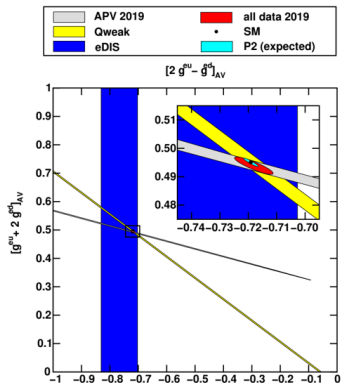
$$a_1 = \frac{6}{5} [2C_{1u} \quad C_{1d}] \quad a_3 = \frac{6}{5} [2C_{2u} \quad C_{2d}]$$

Current Knowledge on $\sin^2 \theta_W$



Current Knowledge on $C_{1q}; C_{2q}$

All 68% C.L. limit



<https://arxiv.org/abs/2103.12555>

D. Wang et al. Nature, Feb. 2014

PVDIS Fitting Formalism

To fit simulated SoLID data at 11, 22 GeV, use alternate expression for A_{PV} in terms of **Parton Distribution Functions (PDFs)**

$$A_{RL;d}^{e;PVDIS} = \frac{3G_F Q^2}{2^{\frac{1}{2}}} \frac{2(1+R_C)C_{1u} (1+R_S)C_{1d} + Y[2C_{2u}(1+c) C_{2d}(1+s)]R_V}{5+4R_C+R_S}$$

PDFs enter as

$$R_V(x) = \frac{u_V+d_V}{u^++d^+}; \quad R_C(x) = \frac{2(c+\bar{c})}{u^++d^+}; \quad R_S(x) = \frac{2(s+\bar{s})}{u^++d^+}; \quad c = \frac{2(c-\bar{c})}{u^++d^+} = 0; \quad s = \frac{2(s-\bar{s})}{u^++d^+} = 0$$

Y is a kinematic factor $Y = [1 - (1-y)^2] = [1 + (1-y)^2]$ Y_3

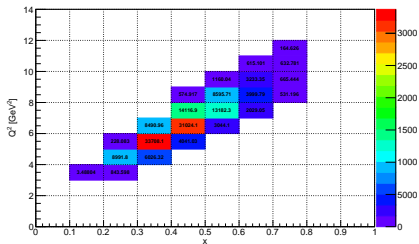
$$\Rightarrow (A_{PV})_b^{SM} [C_{1q}; C_{2q}]; \quad (A_{PV})_b^{SM} \sin^2 \theta_w$$

Use theoretical value $\sin^2 \theta_w = 0.231$

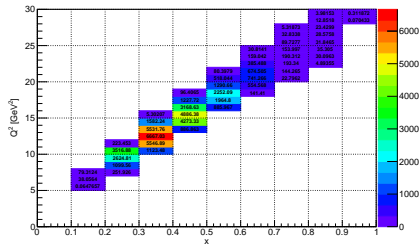
Simulated Event Scattering Rate Extraction

GEMC simulation of 50 A e beam incident on 40cm liquid deuterium target

- Assume 100% beam efficiency
- Scale by trigger efficiency
- DIS kinematic cut: $W > 2$
- Acceptance cut for nominal target position ($z = 10\text{cm}$): $22 < < 35$



Rates (Hz) at 11 GeV



Rates (Hz) at 22 GeV

Uncertainty Contributions to A_{PV}

- Statistical uncertainty

$$dA_{PV}^{\text{stat}} = \frac{1}{P_e \overline{n_b}} = \text{stat};b$$

with $P_e = 0.8$ and bin event count n_b computed from rates for **120 days** of run time

- 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 ($\text{corr}=A = 0.45\%$)

Uncorrelated ($\text{uncorr}=A = 0.28\%$)

Uncertainty Contributions to A_{PV} : Uncertainty Matrix

To account for correlated uncertainties across all fitted bins, must form uncertainty matrix $\Sigma^2 = \Sigma_0^2 + \Sigma_{PDF}^2$:

$$\Sigma_0^2 = \begin{pmatrix} \sigma_1^2 & \dots & 0 \\ \dots & \sigma_2^2 & \dots \\ 0 & \dots & \dots \end{pmatrix} + \begin{pmatrix} \dots & \dots & \dots \\ \dots & \dots & \dots \\ \dots & \dots & \dots \end{pmatrix} \begin{matrix} 1 \\ C \\ C \\ A \\ \vdots \\ C \\ C \\ A \end{matrix}$$

where entries are absolute uncertainties:

$$\sigma_b^2 = (A_{PV})_b^{SM} \frac{\text{corr}}{A} + \sigma_{\text{stat};b}^2 + (A_{PV})_b^{SM} \frac{\text{uncorr}}{A} + \sigma_b^2$$

Uncertainty Contributions to A_{PV} : Uncertainty Matrix

To account for correlated uncertainties across all fitted bins, must form uncertainty matrix $\Sigma^2 = \Sigma_0^2 + \Sigma_{\text{PDF}}^2$:

- Hessian PDF sets:

$$\Sigma_{\text{PDF}}^2_{bb^0} = \frac{1}{4} \sum_{m=1}^{N_{\text{PDF}}=2} (A_{2m;b} \quad A_{2m-1;b})(A_{2m;b^0} \quad A_{2m-1;b^0})$$

- Replica-based PDF sets:

$$\Sigma_{\text{PDF}}^2_{bb^0} = \frac{1}{N_{\text{PDF}}} \sum_{m=1}^{N_{\text{PDF}}} (A_{m;b} \quad A_{0;b})(A_{m;b^0} \quad A_{0;b^0})$$

General Fitting Method

- Generate pseudodata :

$$(A_{PV})_b^{\text{pseudo}} = (A_{PV})_b^{\text{SM}} + r_b \frac{r}{2_{\text{stat};b} + h} + (A_{PV})_b^{\text{SM}} \frac{\text{uncorr}}{A}_b^2 + r^{\theta} (A_{PV})_b^{\text{SM}} \frac{\text{corr}}{A}_b$$

- Minimize χ^2 statistic:

$$\chi^2 = [A^{\text{pseudo}} \quad A^t] [(\Sigma^2)^{-1}] [A^{\text{pseudo}} \quad A^t]^T$$

where e.g. $A^{\text{pseudo}=t} = (A_{PV})_1^{\text{pseudo}=t}, \dots, (A_{PV})_{N_{\text{bin}}}^{\text{pseudo}=t}$

$$(A_{PV})_b^t = (A_{PV})_b^{\text{SM}} \sin^2 \theta_w \left[1 + \frac{HT}{(1-x)^3 Q^2} + \text{CSV} x^2 \right] [C_{1q}; C_{2q}]$$

- See Eq. 2.10 PVDIS Proposal 2010,

<https://hallweb.jlab.org/collab/PAC/PAC35/PR-10-007-SoLID-PVDIS.pdf>

Fitting Results: $\sin^2 \chi_W$

PDF set 12400 CJ15nlo

11 GeV	Stat	Stat	Syst(unc.)	Syst(unc.)	Syst(full)	Syst(full)	All	All
$\sin^2(\chi_W)$	0.230706	0.230308	0.23069	0.230285	0.230743	0.230342	0.230744	0.230343
Error	0.000169517	0.000475106	0.000191799	0.000529134	0.00048733	0.000693488	0.000488029	0.0006953
<i>HT</i>	f	0.000853468	f	0.000531857	f	0.000514219	f	0.000510542
Error	f	0.00427771	f	0.00448832	f	0.00449153	f	0.00449385
<i>CSV</i>	f	-0.0210573	f	-0.019157	f	-0.0190638	f	-0.0190212
Error	f	0.0358759	f	0.0386906	f	0.0387134	f	0.0387554

11 GeV

22 GeV	Stat	Stat	Syst(unc.)	Syst(unc.)	Syst(full)	Syst(full)	All	All
$\sin^2(\chi_W)$	0.231107	0.23049	0.231132	0.23044	0.231223	0.230509	0.231229	0.230507
Error	0.000119778	0.000275762	0.000134687	0.00030585	0.000447761	0.000531413	0.000448918	0.000534493
<i>HT</i>	f	0.0009517	f	0.00113302	f	0.00112616	f	0.00112611
Error	f	0.00162452	f	0.00165647	f	0.00165792	f	0.00165907
<i>CSV</i>	f	-0.0305794	f	-0.0334193	f	-0.0333441	f	-0.0333666
Error	f	0.0137596	f	0.0146806	f	0.0146939	f	0.014755

22 GeV

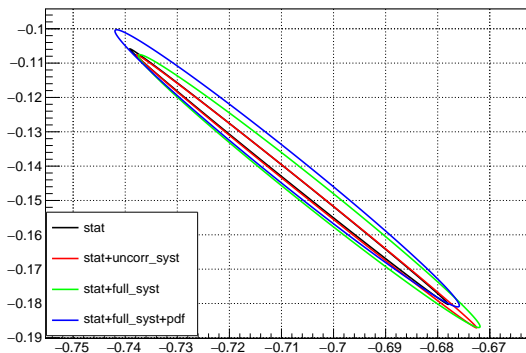
Representing $C_{1q}; C_{2q}$ Error

- Use covariance matrix \mathbf{K} obtained from fitting A_{PV} with

$$HT = CSV = 0$$

- Spectrum of \mathbf{K} determines rotation angle ρ and axes $r_1 = \rho \frac{1}{2}$ and $r_2 = \frac{1}{2}$

11 GeV fit

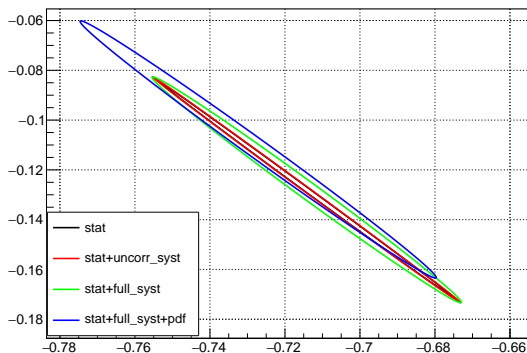


$2C_{2u}$ C_{2d} vs. $2C_{1u}$ C_{1d}

Representing $C_{1q}; C_{2q}$ Error

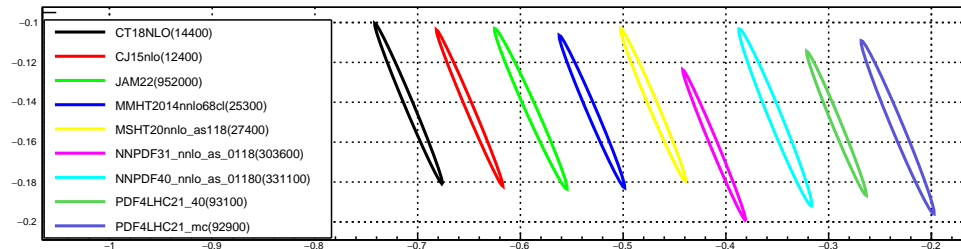
- Use covariance matrix \mathbf{K} obtained from fitting
- Spectrum of \mathbf{K} determines rotation angle ρ and axes $r_1 = \rho \frac{1}{2}$ and $r_2 = \rho \frac{1}{2}$

22 GeV fit



$2C_{2u}$ C_{2d} vs. $2C_{1u}$ C_{1d}

PDF Effects on $C_{1q}; C_{2q}$ for 11 GeV



Side-by-side comparison of uncertainty ellipses for 9 PDF sets

Combined SoLID and P2 Analysis

Perform simultaneous fit of SoLID projections and existing P2 results

- Modify $\chi^2 = (\chi^2)_{\text{SoLID}} + (\chi^2)_{\text{P2}}$:

$$(\chi^2)_{\text{P2}} = \frac{(2C_{1u} \quad C_{1d}) (C_{1q})_{\text{P2}}}{d(C_{1q})_{\text{P2}}} \chi^2$$

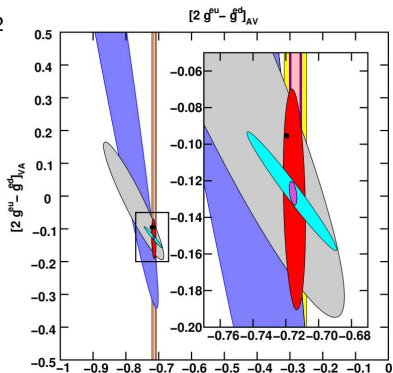
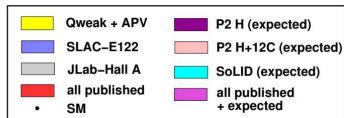
- We use

$$(C_{1q})_{\text{P2}} = \begin{pmatrix} 0.7142 & 0.00236 \\ 0.00236 & 0.00000 \end{pmatrix}$$

from P2 H+ ^{12}C

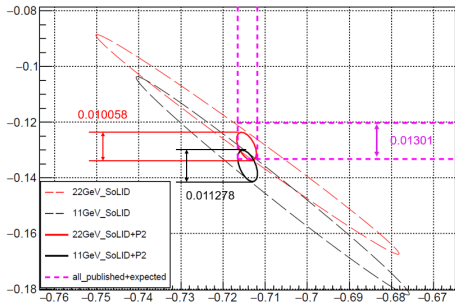
See P2 paper

<https://arxiv.org/pdf/1802.04759.pdf>

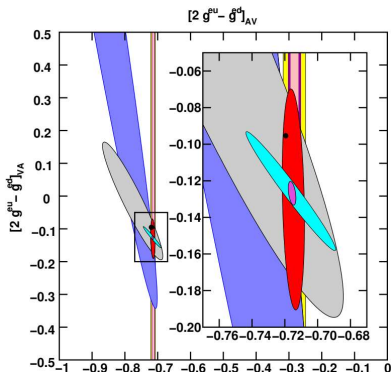
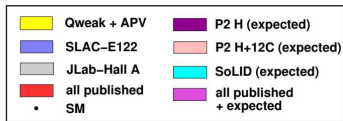


Combined SoLID and P2 Analysis

Perform simultaneous fit of SoLID projections and existing P2 results

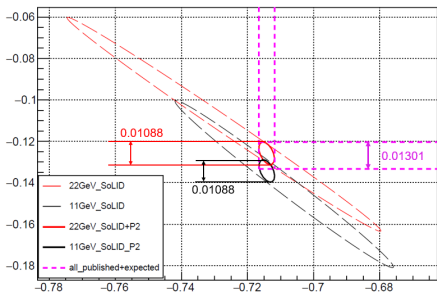


PDF set 12400 (CJ15nlo)

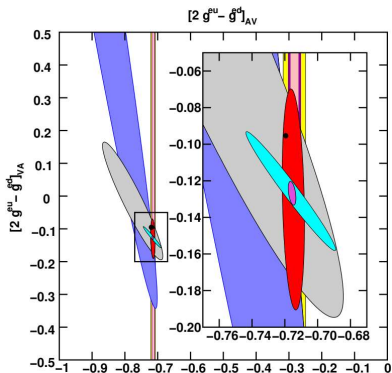
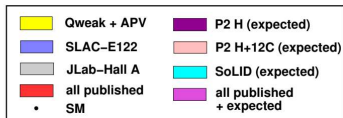


Combined SoLID and P2 Analysis

Perform simultaneous fit of SoLID projections and existing P2 results



PDF set 14400 (CT18NLO)



Remarks: 11 v.s. 22 GeV Comparison

- Small differences only in predicted uncertainties for SM parameters $\sin^2 \theta_W$ and $2C_{iu} - C_{id}$.
 - Decrease in expected uncertainty of $\sin^2 \theta_W$ of $\sim 23\%$
 - Saw decrease of only $\sim 10\%$ in vertical constraint of error ellipse in the best case (CJ15nlo)
 - Major benefit of SoLID over other detectors is ability to constrain $2C_{2u} - C_{2d}$

Acknowledgements

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