SoLID PVDIS on deuteron

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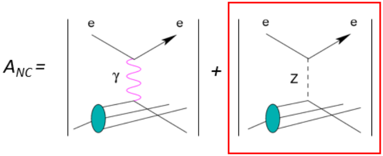
Neutral-Current Weak Interaction in Electron Scattering

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



$$J_\mu^{NC}(l) = \left(\bar{u}_l \gamma_\mu \tfrac{1}{2}(c_V^l - c_A^l \gamma^5) u_l\right)$$

$$-i \frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{M_Z^2}}{q^2 - M_Z^2}$$

$$J_\mu^{NC}(q) = \left(\bar{u}_q \gamma_\mu \tfrac{1}{2}(c_V^q - c_A^q \gamma^5) u_q\right)$$

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

$$L_{NC}^{lq} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{0q} \bar{l}\gamma^\mu l \bar{q}\gamma_\mu q + C_{1q} \bar{e}\gamma^\mu \gamma_5 l \bar{q}\gamma_\mu q + C_{2q} \bar{e}\gamma^\mu e \bar{q}\gamma_\mu \gamma_5 q + C_{3q} \bar{l}\gamma^\mu \gamma_5 l \bar{q}\gamma_\mu \gamma_5 q \right]$$

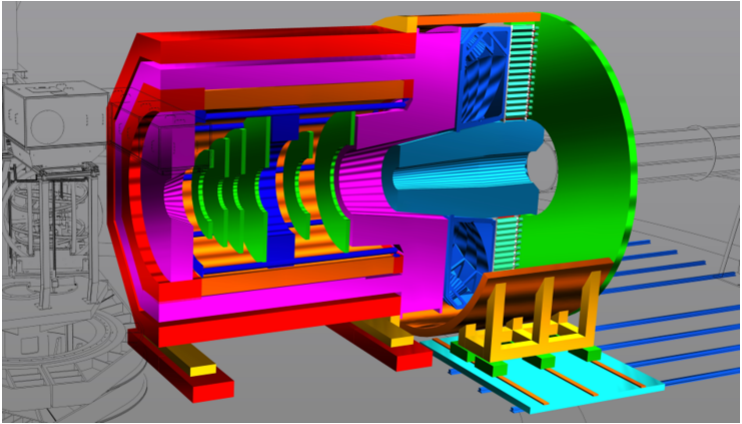
VV | VA, AV (parity-violating) | AA

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

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

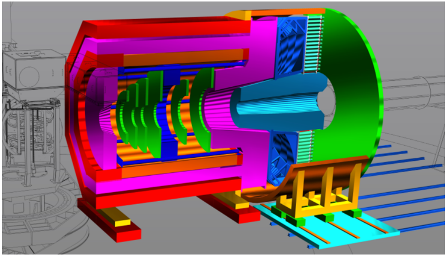
Coherent PVDIS Program with SoLID

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

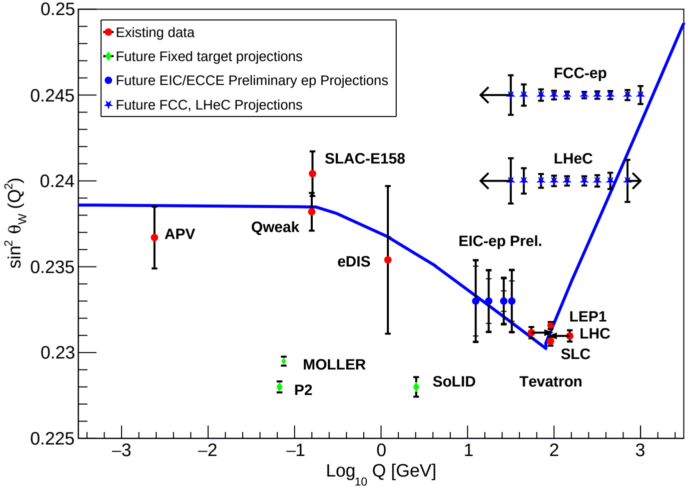
- PVDIS on deuteron:

$$A_{PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)[a_1 Y_1 + a_3 Y_3]$$

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

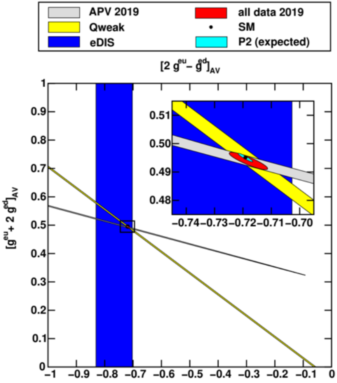
$$a_1 = \frac{6}{5}[2C_{1u} - C_{1d}] \qquad a_3 = \frac{6}{5}[2C_{2u} - C_{2d}]$$

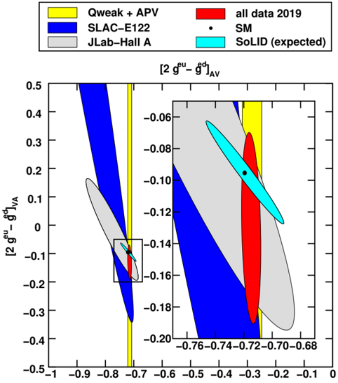
Current Knowledge on $\sin^2\theta_W$



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)

$$A_{RL,d}^{e^-,\mathrm{PVDIS}} = \frac{3G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{2(1+R_C)C_{1u} - (1+R_S)C_{1d} + Y[2C_{2u}(1+\epsilon_c) - C_{2d}(1+\epsilon_s)]R_V}{5+4R_C+R_S}$$

PDFs enter as

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

Y is a kinematic factor $Y \equiv [1-(1-y)^2]/[1+(1-y)^2] \approx Y_3$

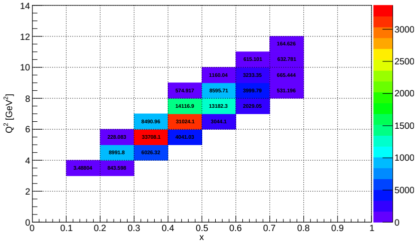
$$\Longrightarrow \quad (A_{\mathrm{PV}})_b^{\mathrm{SM}} [C_{1q}, C_{2q}] \ , \quad (A_{\mathrm{PV}})_b^{\mathrm{SM}} \left[\sin^2\theta_W\right]$$

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

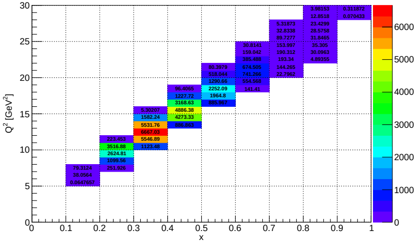
Simulated Event Scattering Rate Extraction

GEMC simulation of 50 μA 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 ($z = 10$cm): $22^\circ < \theta < 35^\circ$



Rates (Hz) at 11 GeV



Rates (Hz) at 22 GeV

Uncertainty Contributions to A_{PV}

- Statistical uncertainty

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

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 ($\sigma_{\mathrm{corr}}/A = 0.45\%$)
Uncorrelated ($\sigma_{\mathrm{uncorr}}/A = 0.28\%$)

Uncertainty Contributions to A_{PV}: Uncertainty Matrix

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

$$\Sigma_0^2 = \begin{pmatrix} \sigma_1^2 & \tilde{\sigma}_1\tilde{\sigma}_2 & \cdots & \tilde{\sigma}_1\tilde{\sigma}_{N_{\mathrm{bin}}} \\ & \sigma_2^2 & \cdots & \tilde{\sigma}_2\tilde{\sigma}_{N_{\mathrm{bin}}} \\ & & \ddots & \vdots \\ & & & \sigma_{N_{\mathrm{bin}}}^2 \end{pmatrix}$$

where entries are absolute uncertainties:

$$\tilde{\sigma}_b = (A_{\mathrm{PV}})_b^{\mathrm{SM}} \left(\frac{\sigma_{\mathrm{corr}}}{A}\right)_b$$

$$\sigma_b^2 = \sigma_{\mathrm{stat},b}^2 + \left[(A_{\mathrm{PV}})_b^{\mathrm{SM}} \left(\frac{\sigma_{\mathrm{uncorr}}}{A}\right)\right]_b^2 + \tilde{\sigma}_b^2$$

Uncertainty Contributions to A_{PV}: Uncertainty Matrix

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

- Hessian PDF sets:

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

- Replica-based PDF sets:

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

General Fitting Method

- Generate pseudodata :

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

- Minimize χ^2 statistic:

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

where e.g. $\mathcal{A}^{\rm pseudo/fit} = \left[(A_{\rm PV})_1^{\rm pseudo/fit}, \ldots, (A_{\rm PV})_{N_{\rm bin}}^{\rm pseudo/fit}\right]$

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

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

- See Eq. 2.10 PVDIS Proposal 2010, https://hallaweb.jlab.org/collab/PAC/PAC35/PR-10-007-SoLID-PVDIS.pdf

Fitting Results: $\sin^2 \theta_W$

PDF set 12400 CJ15nlo

11 GeV	Stat	Stat	Syst(unc.)	Syst(unc.)	Syst(full)	Syst(full)	All	All
$\sin^2(\theta_W)$	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**
β_{HT}	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
β_{CSV}	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

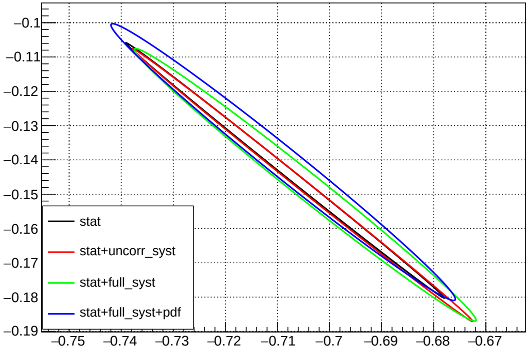
22 GeV	Stat	Stat	Syst(unc.)	Syst(unc.)	Syst(full)	Syst(full)	All	All
$\sin^2(\theta_W)$	0.231107	0.23049	0.231132	0.23044	0.231223	0.230509	0.231229	0.230507
Error	0.000119778	0.000275762	0.000134687	0.00030585	0.000447761	0.000531413	**0.000448918**	**0.000534493**
β_{HT}	f	0.0009517	f	0.00113302	f	0.00112616	f	0.00112611
Error	f	0.00162452	f	0.00165647	f	0.00165792	f	0.00165907
β_{CSV}	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 **K** obtained from fitting A_{PV} with $\beta_{HT} = \beta_{CSV} = 0$
- Spectrum of **K** determines rotation angle ϕ and axes $r_1 = \sqrt{\lambda_1}$ and $r_2 = \sqrt{\lambda_2}$

11 GeV fit

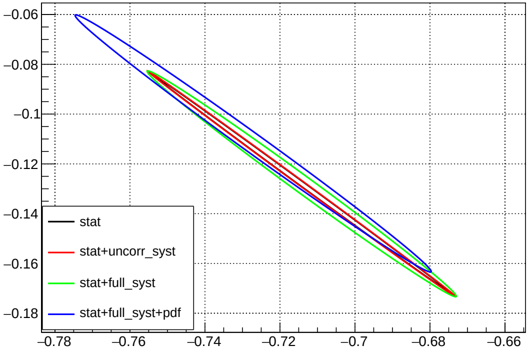


$2C_{2u} - C_{2d}$ vs. $2C_{1u} - C_{1d}$

Representing C_{1q}, C_{2q} Error

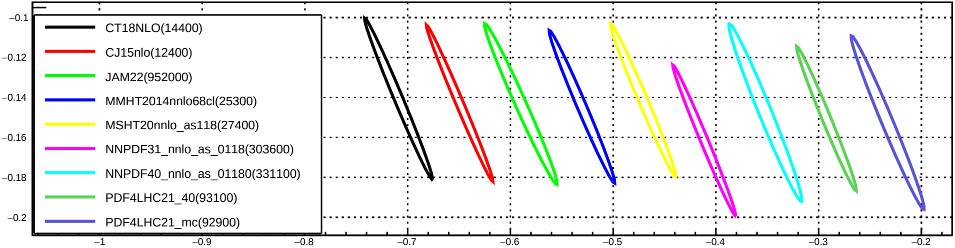
- Use covariance matrix **K** obtained from fitting
- Spectrum of **K** determines rotation angle ϕ and axes $r_1 = \sqrt{\lambda_1}$ and $r_2 = \sqrt{\lambda_2}$

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

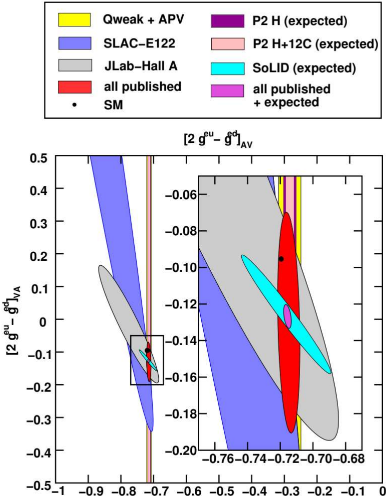
Perform simultaneous fit of SoLID projections and existing P2 results

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

$$(\chi^2)_{\mathrm{P2}} = \left[\frac{(2C_{1u} - C_{1d}) - (C_{1q})_{\mathrm{P2}}}{d(C_{1q})_{\mathrm{P2}}}\right]^2$$

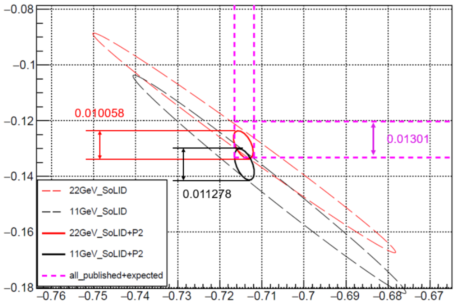
- We use $(C_{1q})_{\mathrm{P2}} = -0.7142 \pm 0.00236$ from P2 H+ ^{12}C

See P2 paper
https://arxiv.org/pdf/1802.04759.pdf

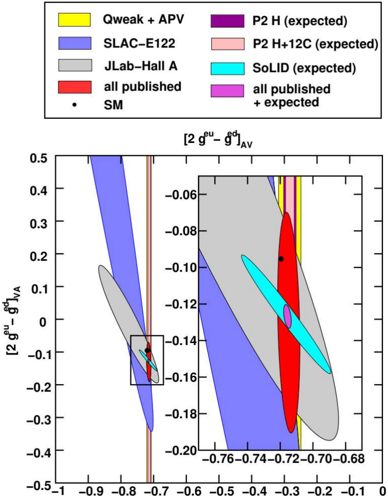


Combined SoLID and P2 Analysis

Perform simultaneous fit of SoLID projections and existing P2 results



PDF set 12400 (CJ15nlo)



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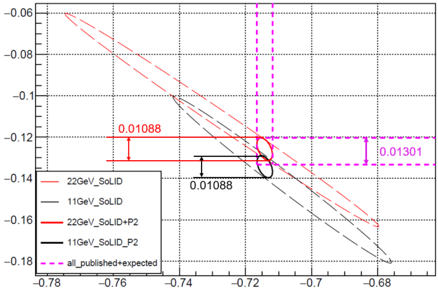
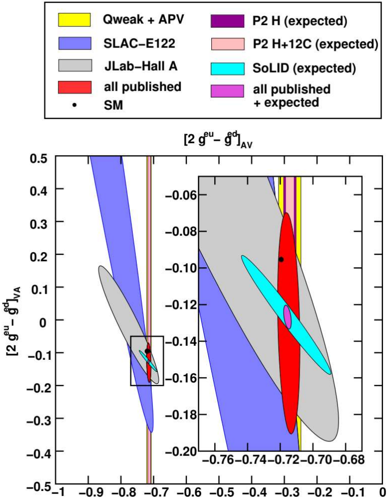


PDF set 14400 (CT18NLO)



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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