PVDIS at 22 GeV

Science at the Luminosity Frontier

Michael Nycz[1]

Alex Emmert [1] **George Evans** [2] Xiaochao Zheng [1]

[1] University of Virginia

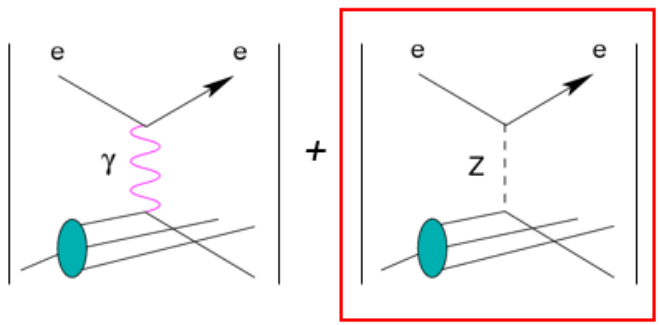
[2] Brigham Young University, DOE SULI summer 2022

January 25, 2023

Outline

Neutral-Current Weak Interaction in Electron Scattering

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

$A_{NC} =$ 

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

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

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

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

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

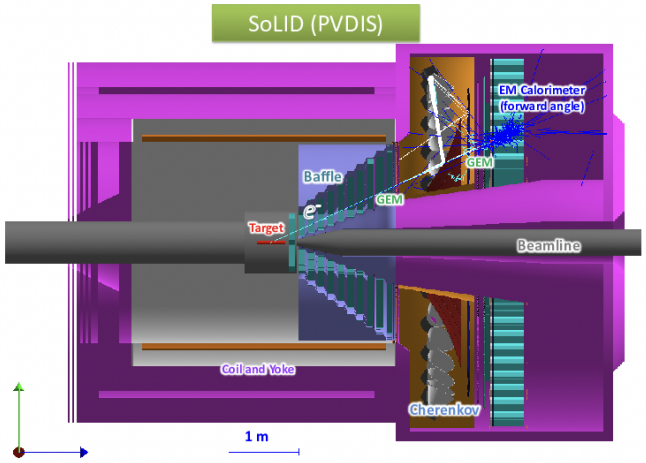
VV VA, AV (parity-violating) AA

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

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

PVDIS Program with SoLID at JLab

SoLID spectrometer: PVDIS configuration



Fully approved 12 GeV experiments:

- PVDIS: E12-10-007
- SIDIS
- J/Psi production
- ...and more

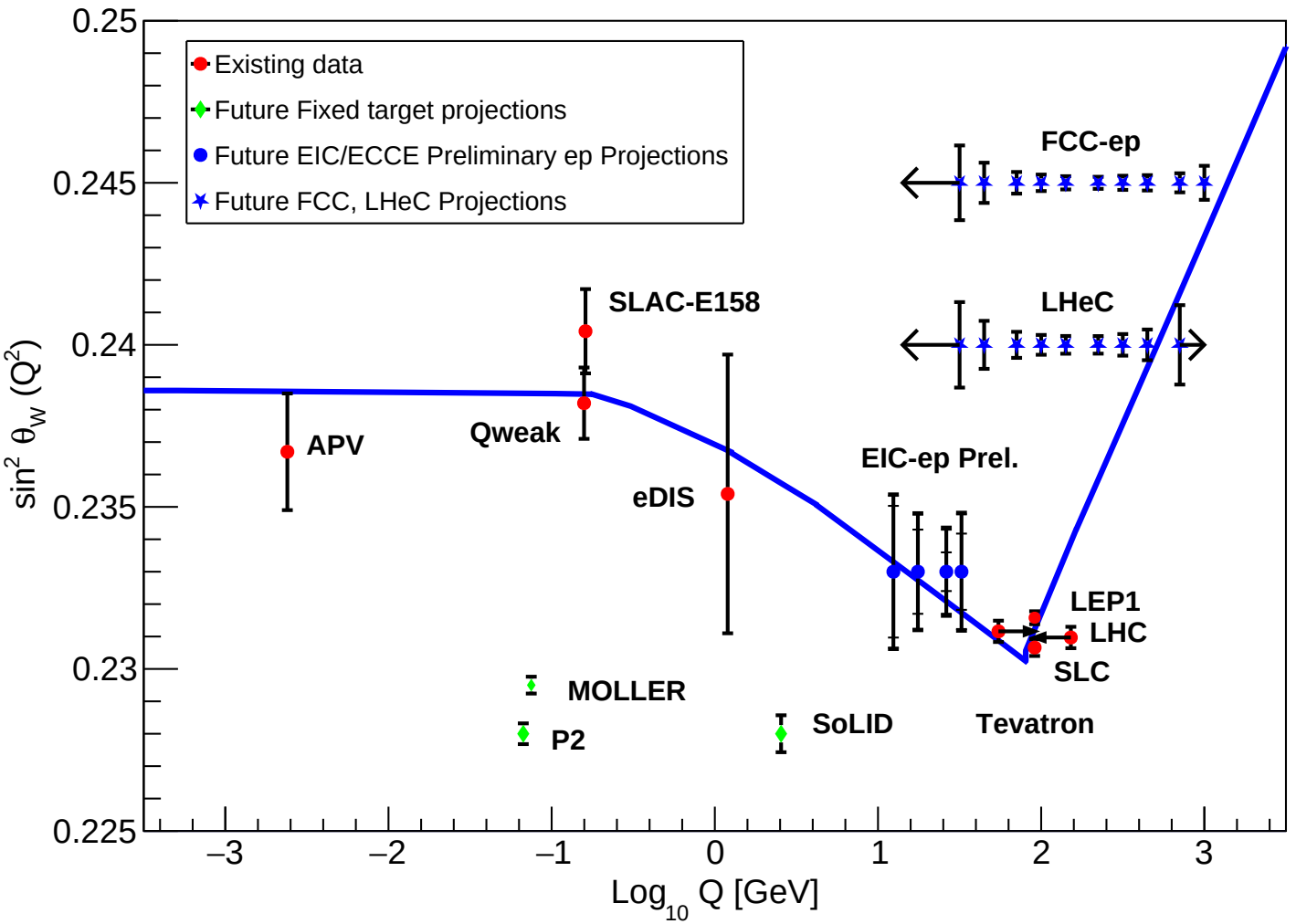
- PVDIS on (isoscalar) deuteron:

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

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

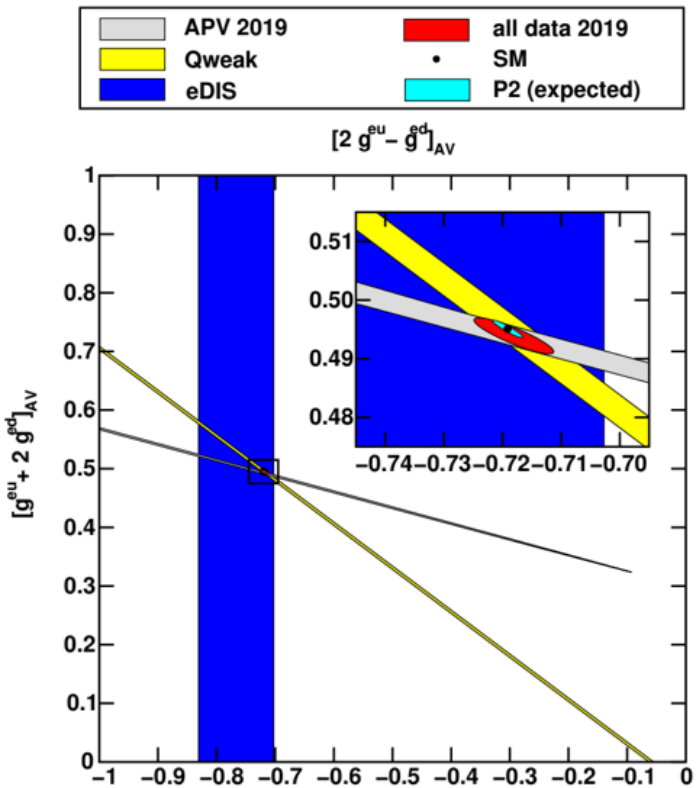
$$a_1 = \frac{6}{5}[2C_{1u} - C_{1d}] \qquad a_3 = \frac{6}{5}[2C_{2u} - C_{2d}]$$

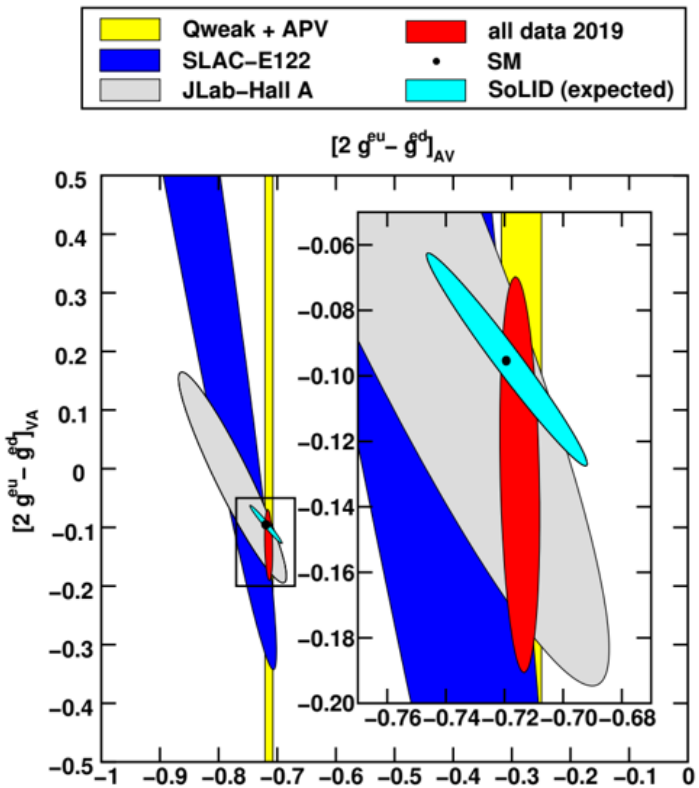
Current Knowledge on $\sin^2\theta_W$



Current Knowledge on C_{1q}, C_{2q}

All 68% C.L. limit





Phys. J. A 57 (3, 2021) 173

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

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

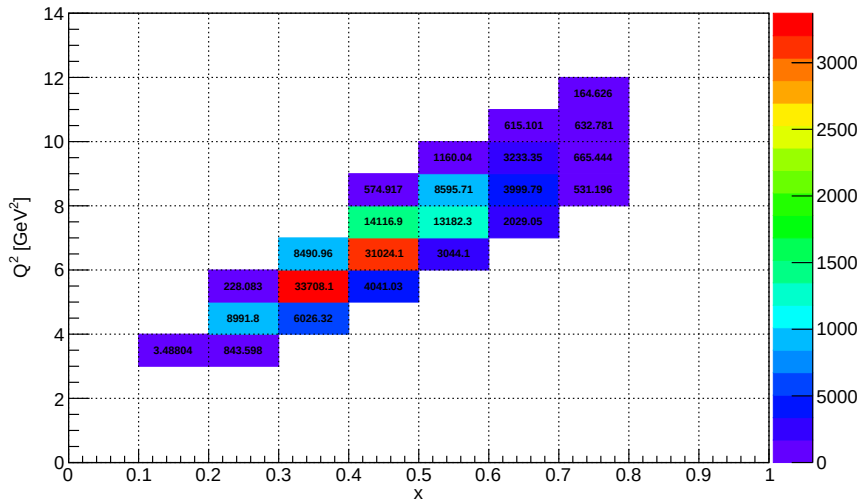
Y is a kinematic factor $Y \equiv [1-(1-y)^2]/[1+(1-y)^2] \approx Y_3$

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

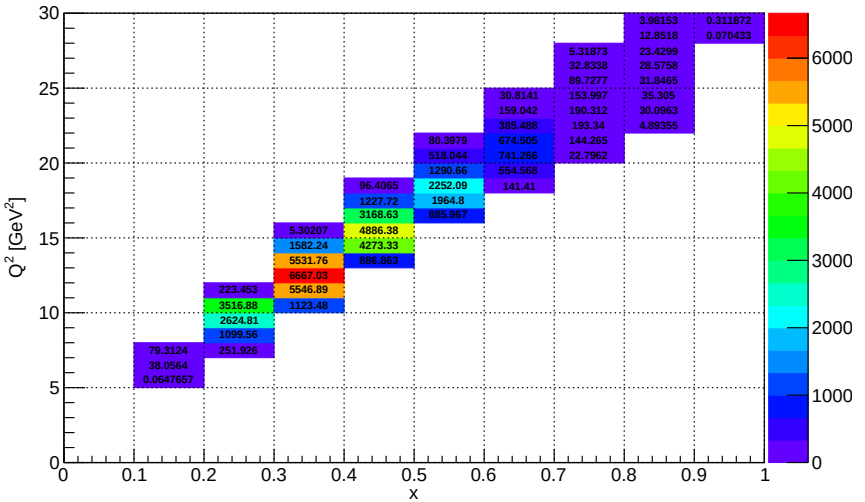
Event Simulation: Scattering Rate

GEMC simulation: 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

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

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

Uncertainty Contributions to A_{PV}: Uncertainty Matrix

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

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

where entries are absolute uncertainties:

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

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

Uncertainty Contributions to A_{PV}: Uncertainty Matrix

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

- Hessian PDF sets:

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

- Replica-based PDF sets:

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

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

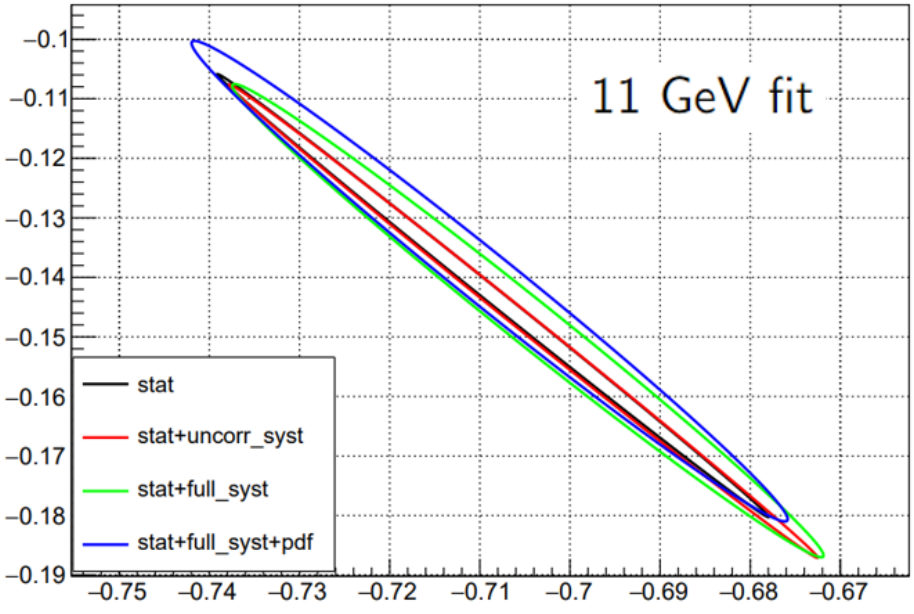
11 GeV	Stat	Stat	Syst(unc.)	Syst(unc.)	Syst(full)	Syst(full)	All	All
$\sin^2(\theta_W)$	0.230706	0.230308	0.23069	0.230285	0.230743	0.230342	0.230744	0.230343
Error	0.000169517	0.000475106	0.000191799	0.000529134	0.00048733	0.000693488	**0.000488029**	**0.0006953**
β_{HT}	f	0.000853468	f	0.000531857	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

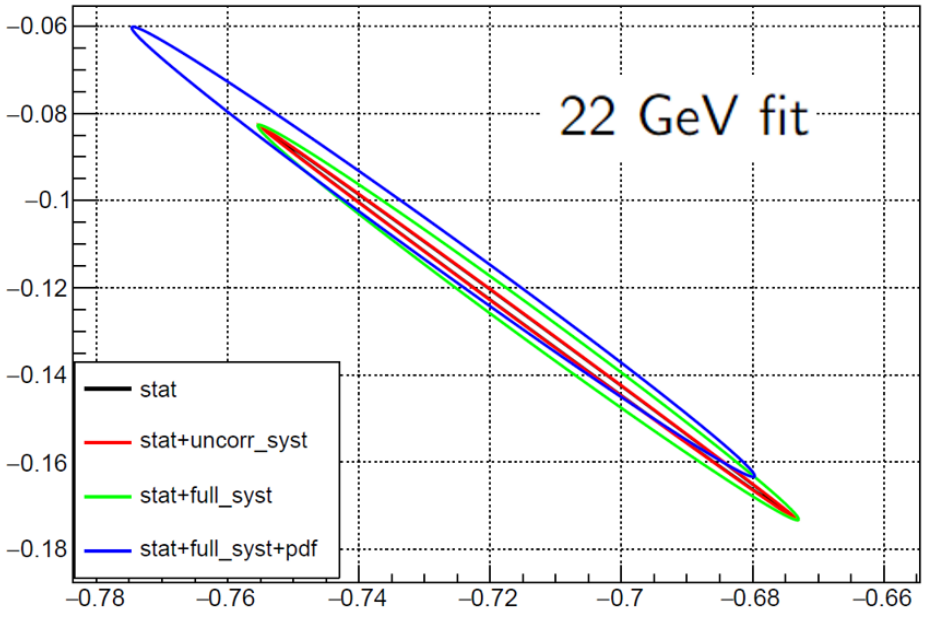
11 GeV

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





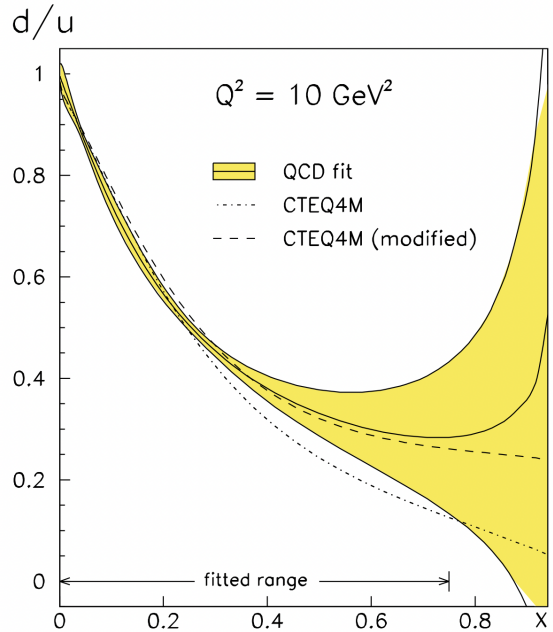
$2C_{2u} - C_{2d}$ vs. $2C_{1u} - C_{1d}$

- 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 $r_2 = \sqrt{\lambda_2}$

SoLID PVDIS: Proton: d/u at large x

d/u at high x

- Discriminate nuclear structure models (SU6, pQCD, etc...)
  - Large uncertainties at high x due to deuteron nuclear corrections

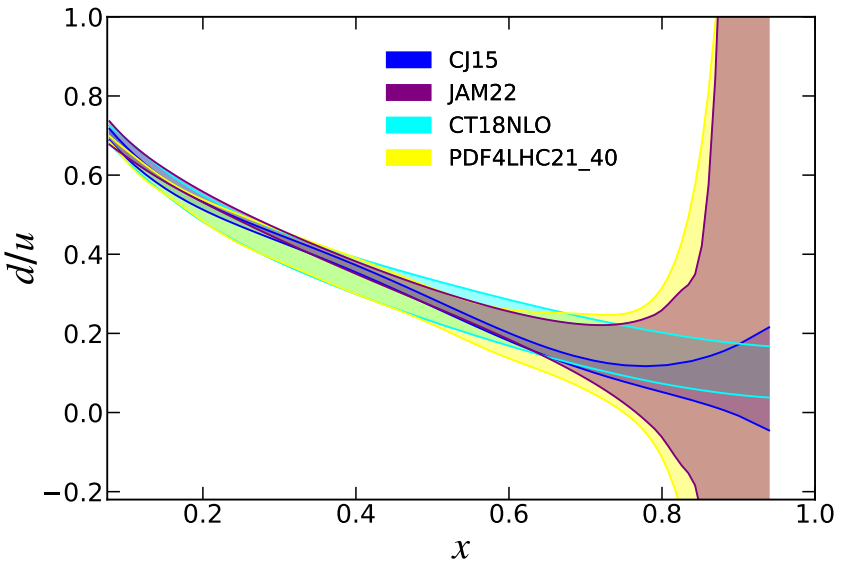


M. Botje, Eur. Phys. J. C14 (2000)

SoLID PVDIS: Proton: d/u at large x

d/u at high x

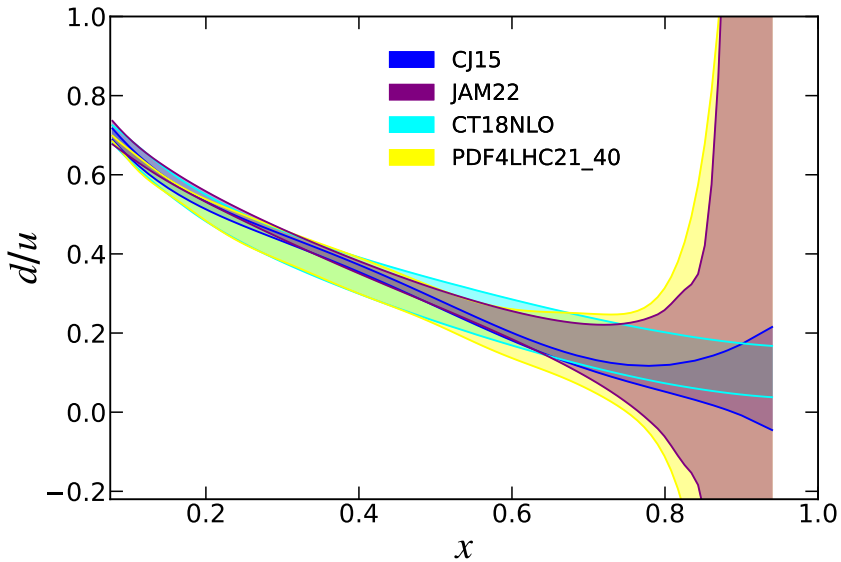
- Discriminate nuclear structure models (SU6, pQCD, etc...)
  - Large uncertainties at high x due to deuteron nuclear corrections
- Attempts to reduce uncertainties due to nuclear corrections
  - BoNus: Spectator tagging of Barely Off-Shell Neutrons
  - MARATHON: Ratio of A=3 nuclei



SoLID PVDIS: Proton: d/u at large x

d/u at high x

- Discriminate nuclear structure models (SU6, pQCD, etc...)
  - Large uncertainties at high x due to deuteron nuclear corrections
- Attempts to reduce uncertainties due to nuclear corrections
  - BoNus: Spectator tagging of Barely Off-Shell Neutrons
  - MARATHON: Ratio of A=3 nuclei
- **PVDIS using proton target provides an alternative way of accessing d/u at large x**
  - **Extraction would eliminate nuclear corrections**



PVDIS: d/u

$$A_{\mathrm{RL,\ p}}^{e-,\mathrm{PVDIS}} = |P_{\mathrm{beam}}| \frac{3\sqrt{2}G_{\mathrm{F}}Q^2}{4\pi\alpha} \frac{[2(u^+ + c^+)C_{1u} - (d^+ + s^+)C_{1d}] + Y[2(u_{\mathrm{V}} + c_{\mathrm{V}})C_{2u} - (d_{\mathrm{V}} + s_{\mathrm{V}})C_{2d}]}{4[u^+ + c^+] + [d^+ + s^+]}$$

- Assume contribution of sea quarks to be negligible

$$A_{\mathrm{PV}} = |P_{\mathrm{beam}}| \frac{3\sqrt{2}G_{\mathrm{F}}Q^2}{4\pi\alpha} \frac{[2u_{\mathrm{V}}C_{1u} - d_{\mathrm{V}}C_{1d}] + Y[2u_{\mathrm{V}}C_{2u} - d_{\mathrm{V}}C_{2d}]}{4u_{\mathrm{V}} + d_{\mathrm{V}}}$$

$$\Rightarrow \frac{d_{\mathrm{V}}}{u_{\mathrm{V}}} = \frac{-4A_{\mathrm{PV}} + 2C_{\mathrm{p}}C_{1u} + 2C_{\mathrm{p}}C_{2u}Y}{A_{\mathrm{PV}} + C_{\mathrm{p}}C_{1d} + C_{\mathrm{p}}C_{2d}Y}$$

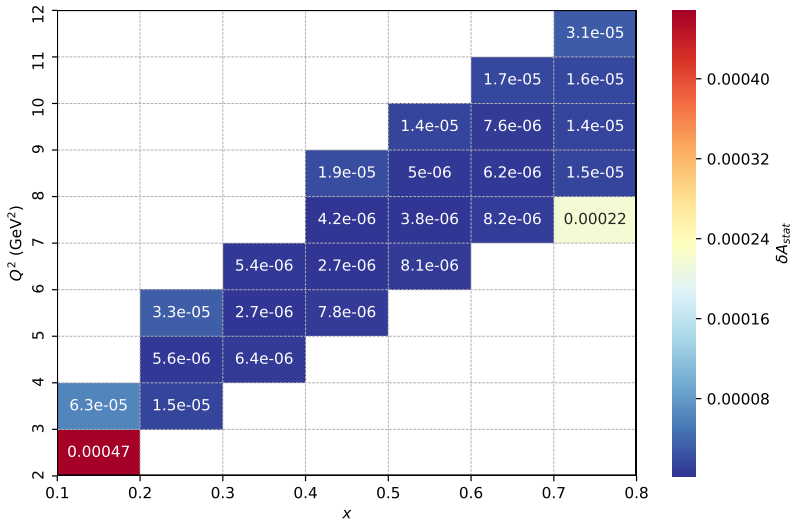
where

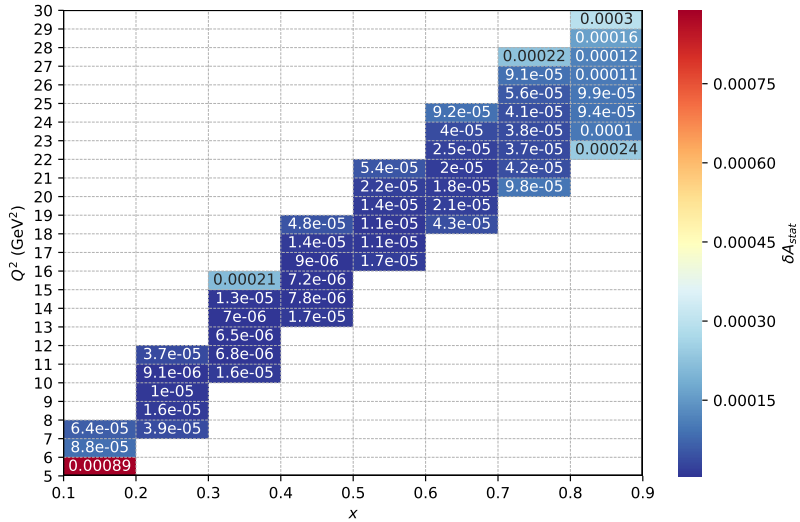
$$C_{\mathrm{p}} = |P_{\mathrm{beam}}| \frac{3\sqrt{2}G_{\mathrm{F}}Q^2}{4\pi\alpha}$$

PVDIS Study on Proton using SoLID

- Simulated 90 days
- 50 μA
- 40-cm liquid hydrogen target
- W>2 GeV and $22^\circ \leq \theta \leq 35^\circ$

Same as 11 GeV proton experimental run





Rates (Hz) at 11 and 22 GeV

Generate Pseudo-data

$$(A_{\mathrm{PV}})_b^{\mathrm{pseudo}} = (A_{\mathrm{PV}})_b^{\mathrm{theory}} + r_b\sqrt{(\delta A_{\mathrm{PV}})^2_{\mathrm{stat},b} + (\delta A_{\mathrm{PV}})^2_{\text{sys uncor},b}} + r'\sqrt{(\delta A_{\mathrm{PV}})^2_{\text{sys cor},b}}$$

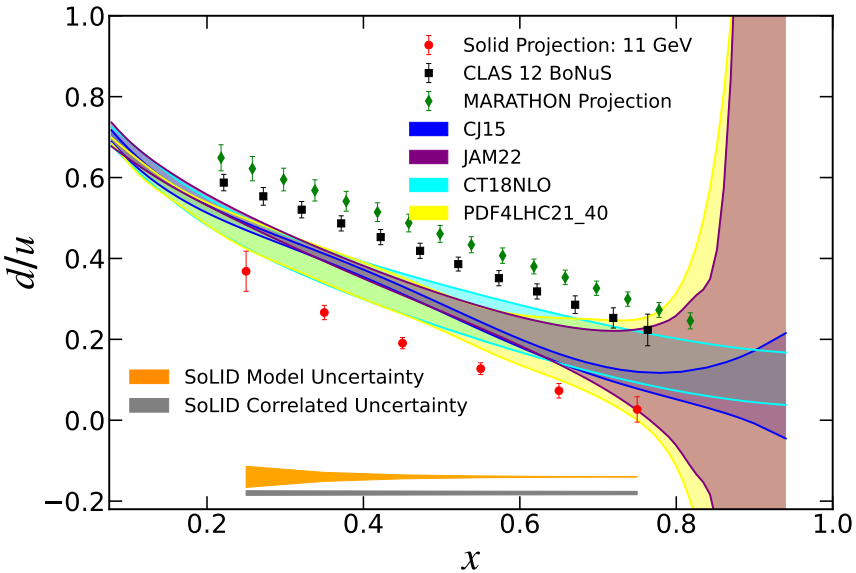
Extract d/u

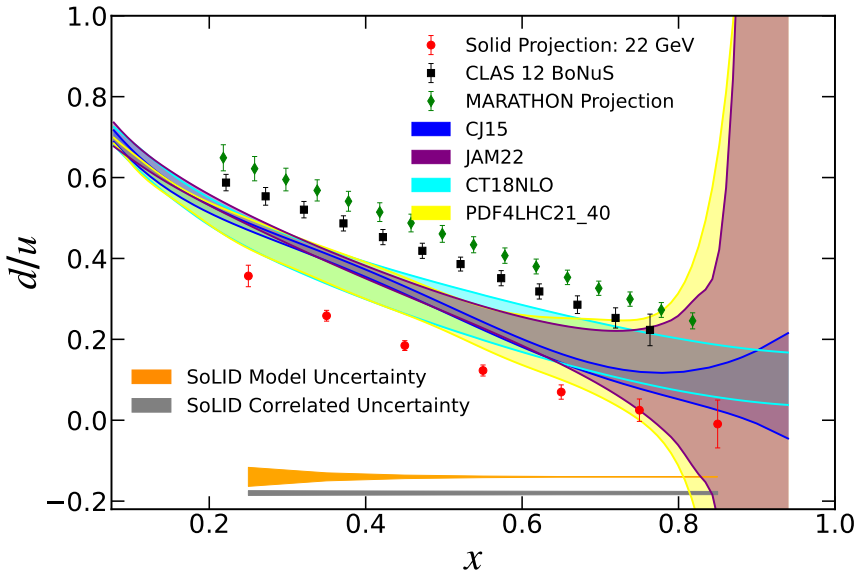
$$\frac{d_{\mathrm{V}}}{u_{\mathrm{V}}} = \frac{-4A_{\mathrm{PV}} + 2C_{\mathrm{p}}C_{1u} + 2C_{\mathrm{p}}C_{2u}Y}{A_{\mathrm{PV}} + C_{\mathrm{p}}C_{1d} + C_{\mathrm{p}}C_{2d}Y}$$

Uncertainties

1. Statistical
2. Experimental
3. PDF uncertainties
   - PDF4LHC21 40, CT18NLO, NNPDF40 nlo as 0118

Results: d/u





Extracted d/u for 11 and 22 GeV

Summary and Outlook: PVDIS at 22 GeV with SoLID

PVDIS deuteron at 22 GeV with SoLID

- 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 $2C_{2u} - C_{2d}$

PVDIS Proton at 22 GeV with SoLID

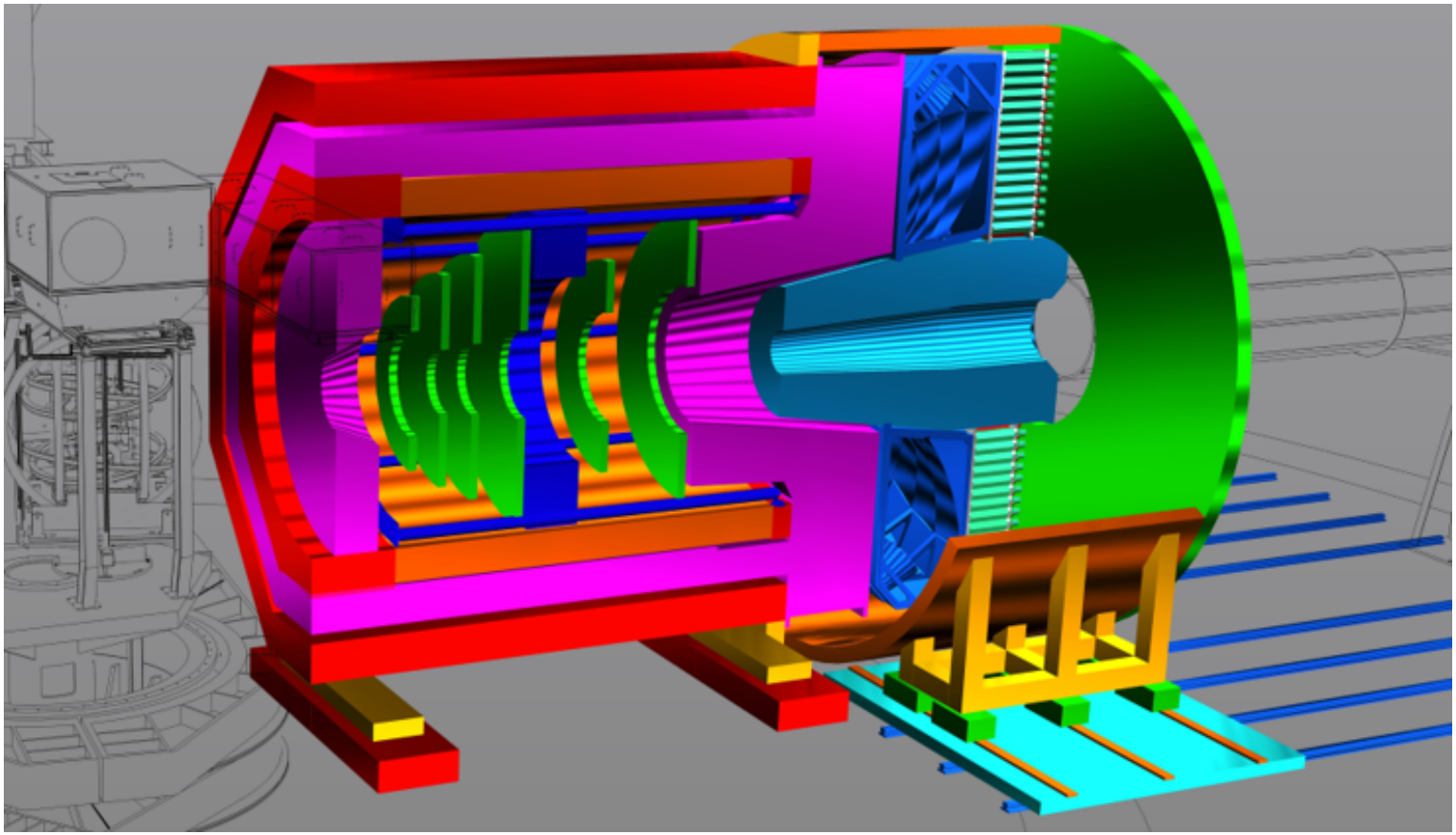
- Alternative method to extract d/u
- Free of nuclear corrections
- Opportunity to push high in x ≈ 0.85

Acknowledgements

- Alex Emmert's research in summer 2022 was supported by Mitchell summer fellowship, Department of Physics, University of Virginia
- George Evans' research in summer 2022 was supported by Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program

PVDIS Program with SoLID at JLab

[noframenumbering] Solenoid Large-Intensity Device (SoLID) spectrometer



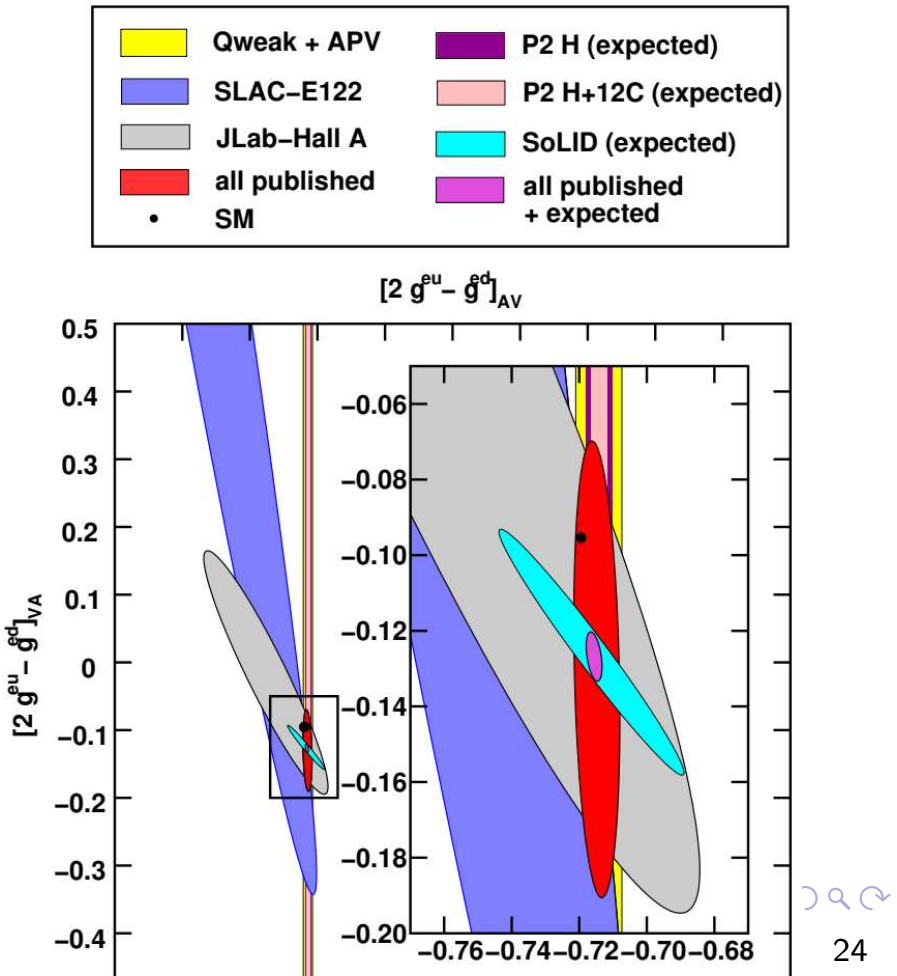
Combined SoLID and P2 Analysis

[noframenumbering] Perform simultaneous fit of SoLID projections and expected P2 results

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

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

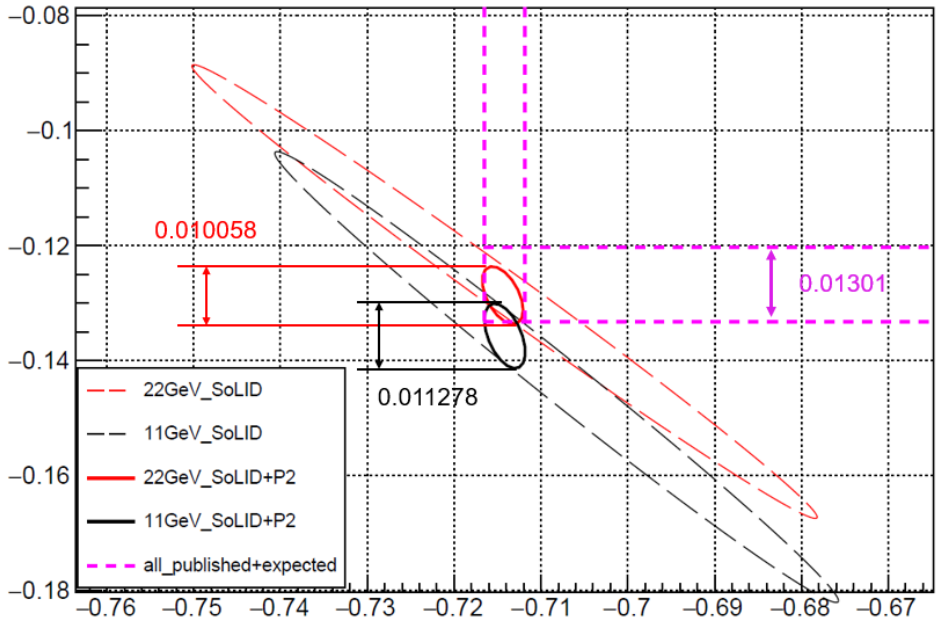
- We use
  $(C_{1q})_{\mathrm{P2}} = -0.7142 \pm 0.00236$
  from P2 H+ ^{12}C



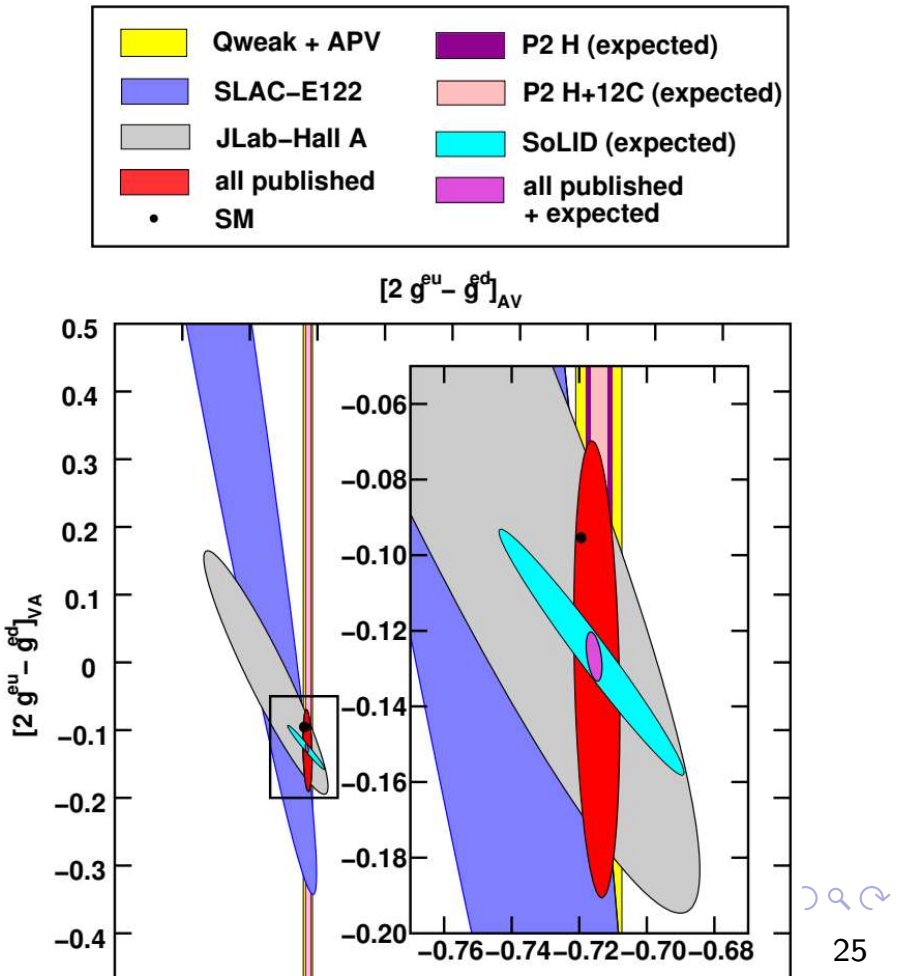
Overview of P2 Experiment
https://arxiv.org/pdf/1802.04759.pdf

Combined SoLID and P2 Analysis

[noframenumbering] Perform simultaneous fit of SoLID projections and epected P2 results

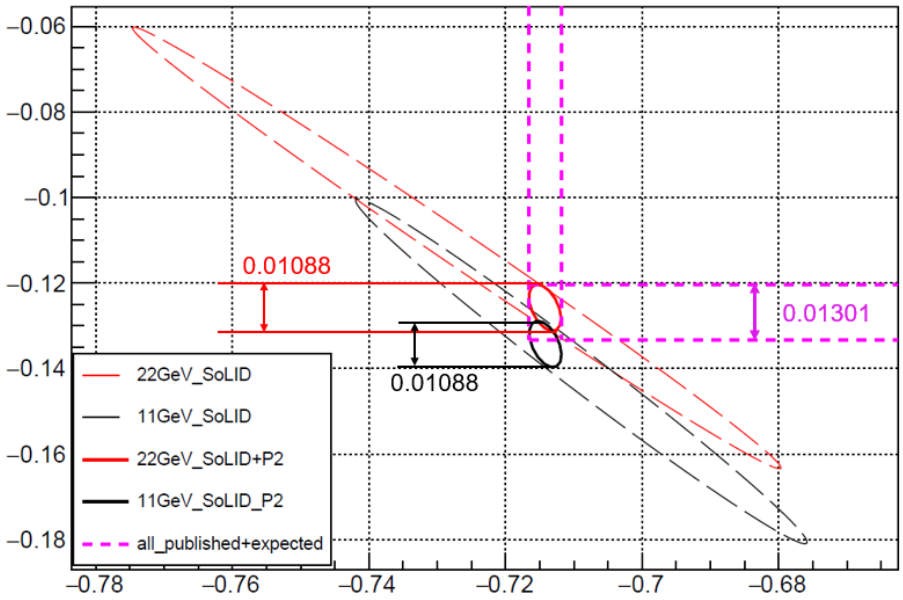


PDF set 12400 (CJ15nlo)



Combined SoLID and P2 Analysis

[noframenumbering] Perform simultaneous fit of SoLID projections and existing P2 results



PDF set 14400 (CT18NLO)