Neutral-Current Electroweak Physics with SoLID and a positron beam at JLab

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March 7th, 2023

Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

https://arxiv.org/abs/2007.15081

An experimental program with high duty-cycle polarized and unpolarized positron beams at Jefferson Lab

Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

https://arxiv.org/abs/2103.12555

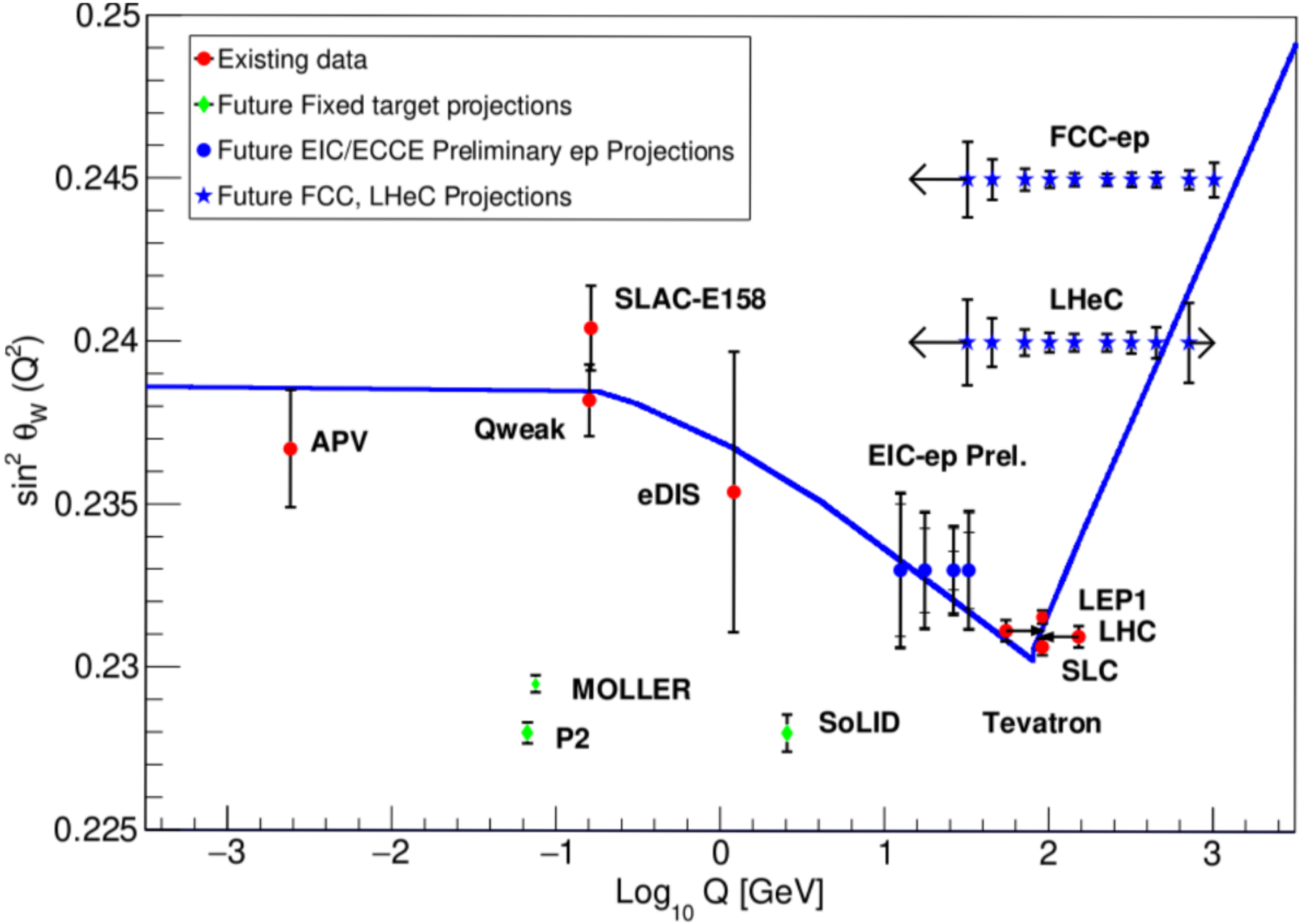
Accessing weak neutral-current coupling g_{AA}^{eq} using positron and electron beams at Jefferson Lab

(A New Proposal to Jefferson Lab PAC-49)

Measurement of the Asymmetry $A_d^{e^+e^-}$ between $e^+-{}^2$H and $e^--{}^2$H Deep Inelastic Scattering Using SoLID and PEPPo at JLab

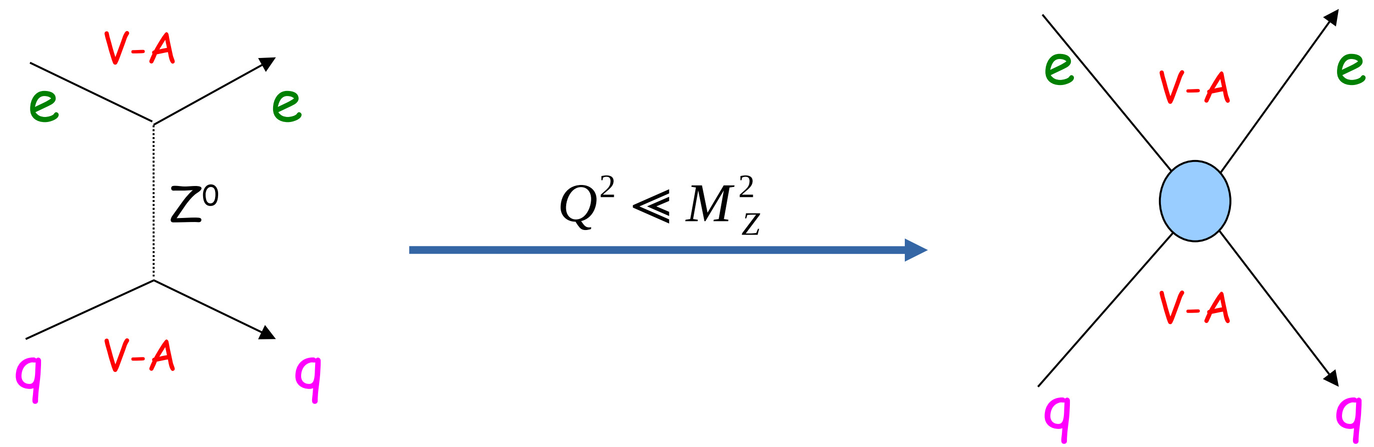
May 24, 2021

The Landscape of (Neutral-Current) Electroweak Study



EIC projections from arxiv.org/2204.07557 [hep-ph]
LHeC projection (60GeV x 7 TeV, ~1000fb^{-1}) from EPJC 80 (2020) 9, 831 arxiv.org/2007.11799;
FCC-ep projections: priv. comm. D. Britzger
(points with uncertainties comparable to or smaller than Qweak are shown, full range shown as arrows)

Neutral-Current Effective Couplings in (Low Energy) Electron Scattering



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

VV (identical to γ) AV, VA (parity-violating) AA

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

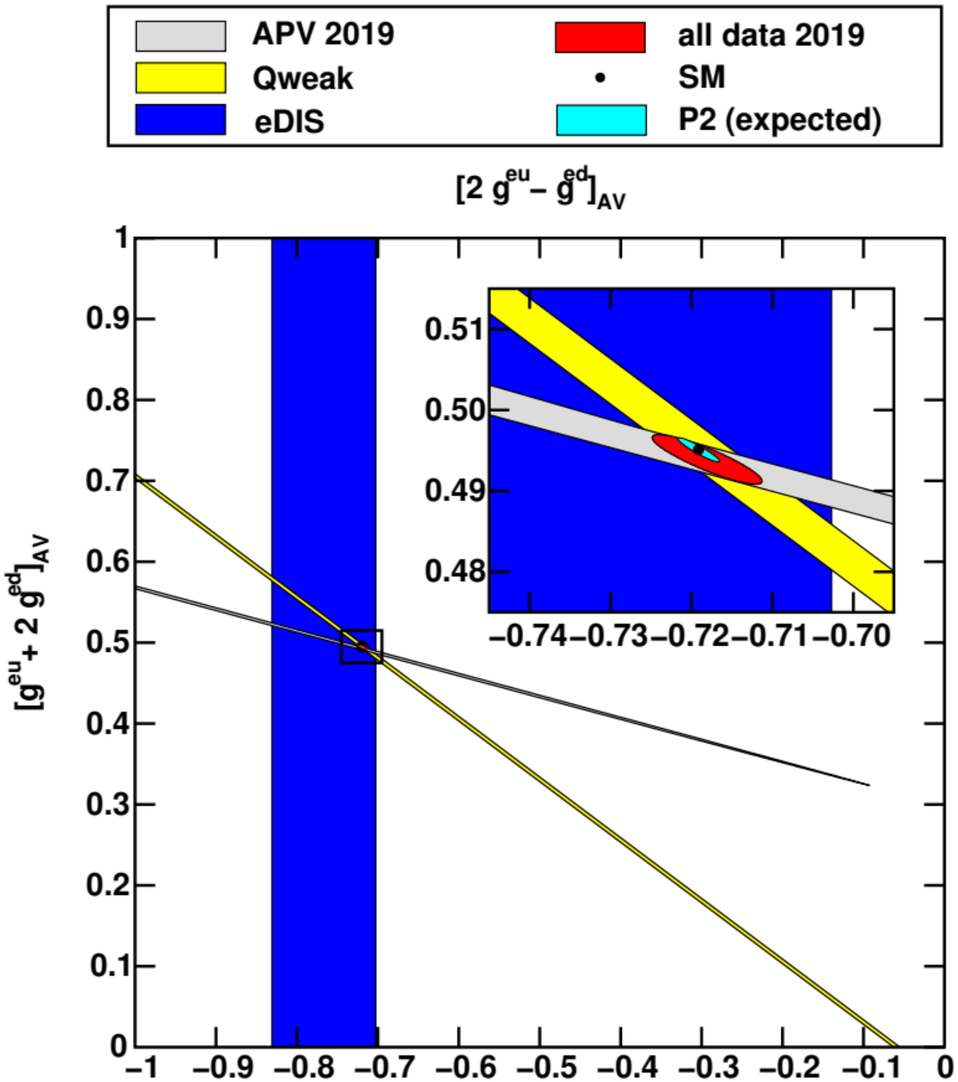
$$C_{1d} = 2 g_A^e g_V^d = \frac{1}{2} - \frac{2}{3} \sin^2(\theta_W) \qquad C_{2d} = 2 g_V^e g_A^d = \frac{1}{2} - 2\sin^2(\theta_W) \qquad C_{3d} = -2 g_A^e g_A^d = -\frac{1}{2}$$

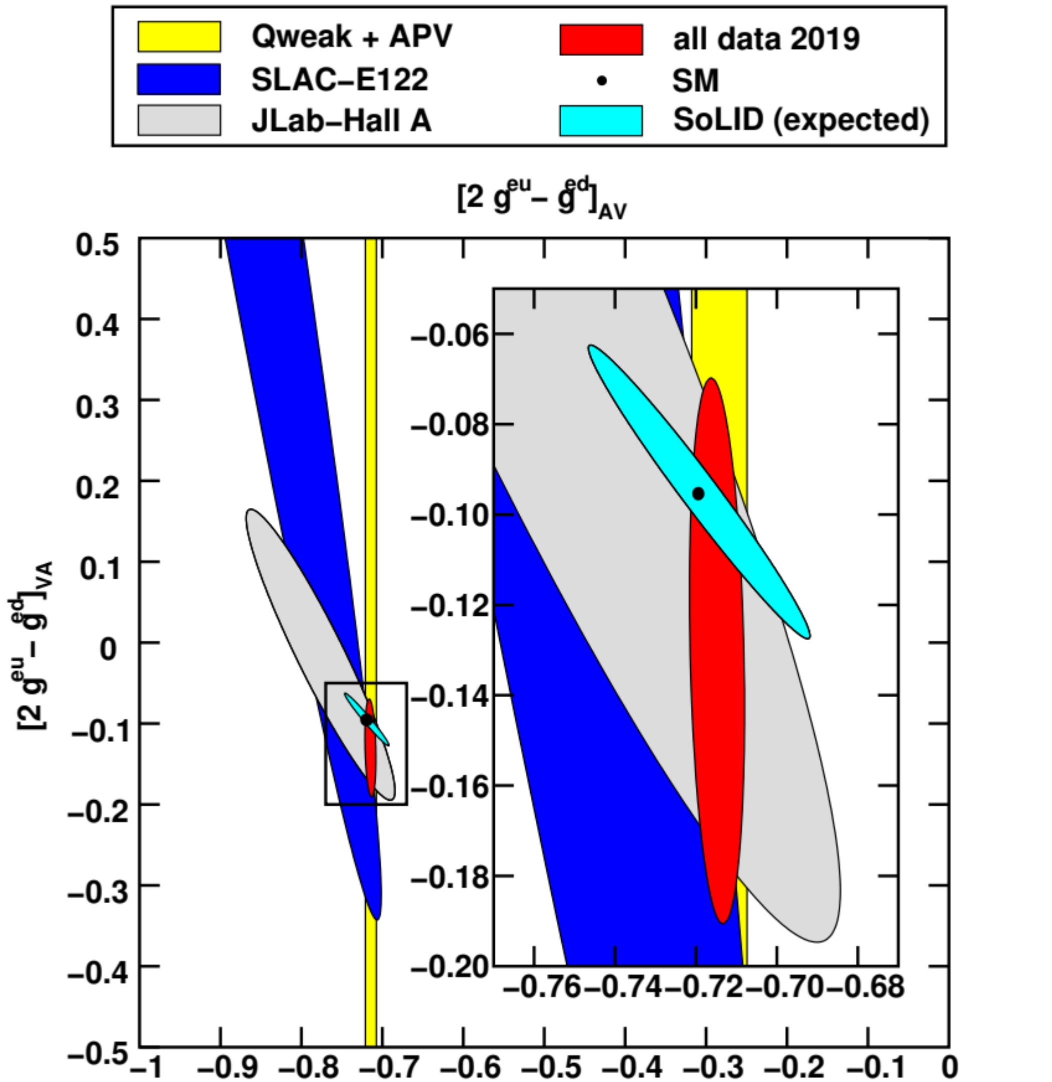
- A new set of notation $g_{AV,VA,AA}^{eq}$ introduced in 2013 – Erler&Su, Prog. Part. Nucl. Phys. 71, 119 (2013)
- Example: In PVES, we can measure $C_{1,2}$

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

all are 68% C.L. limit

https://arxiv.org/abs/2103.12555





CERN for muon: $2C_{3u}^{\mu q} - C_{3d}^{\mu q} = 1.57 \pm 0.38$ Argento et al., PLB120B, 245 (1983)

Positron working group meeting
March 7-8, 2023

In the Parton Model (low energy)

Parity-Violating

$$A_{RL}^{e^{\pm}} = \frac{\sigma_R^{e^{\pm}} - \sigma_L^{e^{\pm}}}{\sigma_R^{e^{\pm}} + \sigma_L^{e^{\pm}}}$$

$$\left(A_{RL}^{e^{\pm}} = -A_{LR}^{e^{\pm}}\right)$$

$$A_d = |\lambda| (108\, ppm) Q^2 \left[(2C_{1u} - C_{1d}) + Y(y)(2C_{2u} - C_{2d}) R_V(x) \right]$$

beam polarization

$$Y(y) = \frac{1-(1-y)^2}{1+(1-y)^2} \qquad R_V(x) = \frac{u_V(x) + d_V(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

(indicates spin flip of quarks)

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(indicates spin flip of quarks)

Lepton-Charge

$$A_{RL}^{e^+ e^-} = \frac{\sigma_R^{e^+} - \sigma_L^{e^-}}{\sigma_R^{e^+} + \sigma_L^{e^-}}$$

$$\left(A_{RL}^{e^+ e^-} \neq -A_{LR}^{e^+ e^-}\right)$$

$$A_{RL,d}^{e^+ e^-} = (108\,ppm)Q^2 Y(y) R_V(x)\left[|\lambda|(2C_{2u} - C_{2d}) - (2C_{3u} - C_{3d})\right]$$

(flip |λ| for LR)

“B” in CERN measurement

$$A_{RR}^{e^+ e^-} = \frac{\sigma_R^{e^+} - \sigma_R^{e^-}}{\sigma_R^{e^+} + \sigma_R^{e^-}}$$

$$\left(A_{RR}^{e^+ e^-} \neq -A_{LL}^{e^+ e^-}\right)$$

$$A_{RR,d}^{e^+ e^-} = (108\,ppm)Q^2\left[|\lambda|(2C_{1u} - C_{1d}) - Y(y) R_V(x)(2C_{3u} - C_{3d})\right]$$

(flip |λ| for LL)

$$A_{unpol}^{e^+ e^-} = \frac{\sigma^{e^+} - \sigma^{e^-}}{\sigma^{e^+} + \sigma^{e^-}} \qquad A_d^{e^+ e^-} = -(108\,ppm)Q^2 Y(y) R_V(x)(2C_{3u} - C_{3d})$$

In the Parton Model (low energy)

Parity-Violating

$$A_{RL}^{e^\pm} = \frac{\sigma_R^{e^\pm} - \sigma_L^{e^\pm}}{\sigma_R^{e^\pm} + \sigma_L^{e^\pm}}$$

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(indicates spin flip of quarks)

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(flip $|\lambda|$ for LR)

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$$A_{RR}^{e^+e^-} = \frac{\sigma_R^{e^+} - \sigma_R^{e^-}}{\sigma_R^{e^+} + \sigma_R^{e^-}}$$

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(flip $|\lambda|$ for LL)

$$\left(A_{RR}^{e^+e^-} \neq -A_{LL}^{e^+e^-}\right)$$

(no polarization needed!)

$$A_{unpol}^{e^+e^-} = \frac{\sigma^{e^+} - \sigma^{e^-}}{\sigma^{e^+} + \sigma^{e^-}}$$

$$A_d^{e^+e^-} = -(108\,ppm)Q^2 Y(y) R_V(x)(2C_{3u} - C_{3d})$$

“direct” access to $2C_{3u}$-C_{3d}

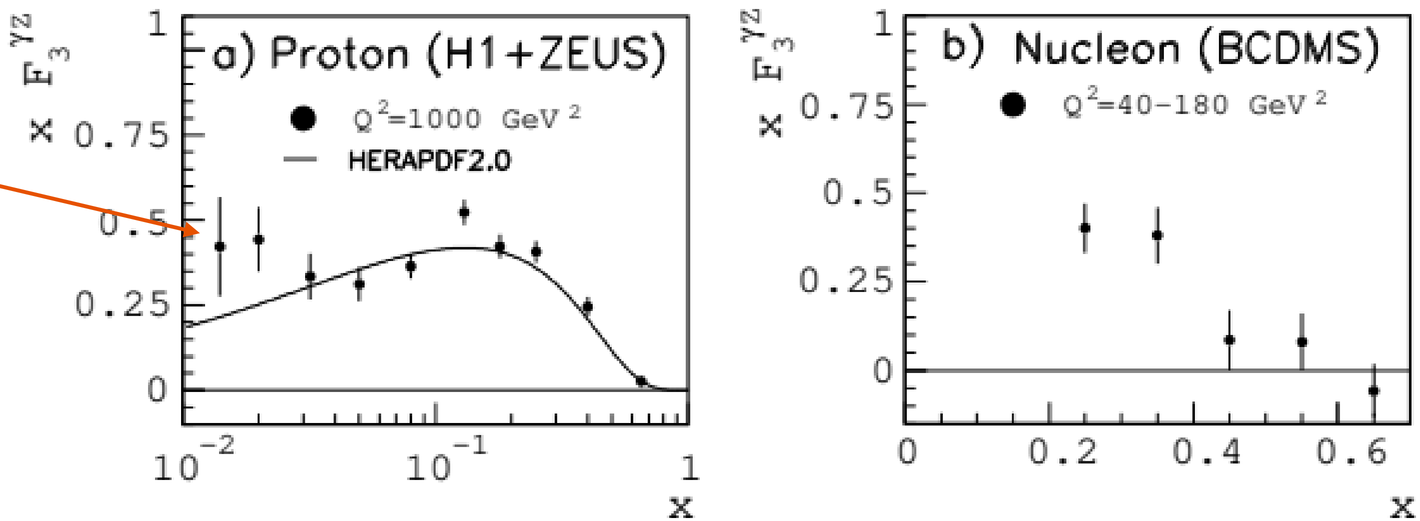
e^+e^- for Structure Function Study

Approximately: $A^{e^+ e^-}_{\text{unpol}} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{g_A^e}{2} Y(y) \frac{F_3^{\gamma Z}}{F_1^{\gamma}}$ (in Apv, $F_3^{\gamma Z}$ is suppressed by g_V^e)

In the parton model: $F_1^{\gamma}(x, Q^2) = 1/2 \sum Q_q^2 [q + \bar{q}]$ $F_3^{\gamma Z}(x, Q^2) = 2 \sum g_A^q [q - \bar{q}]$

Low x HERA data pose question on

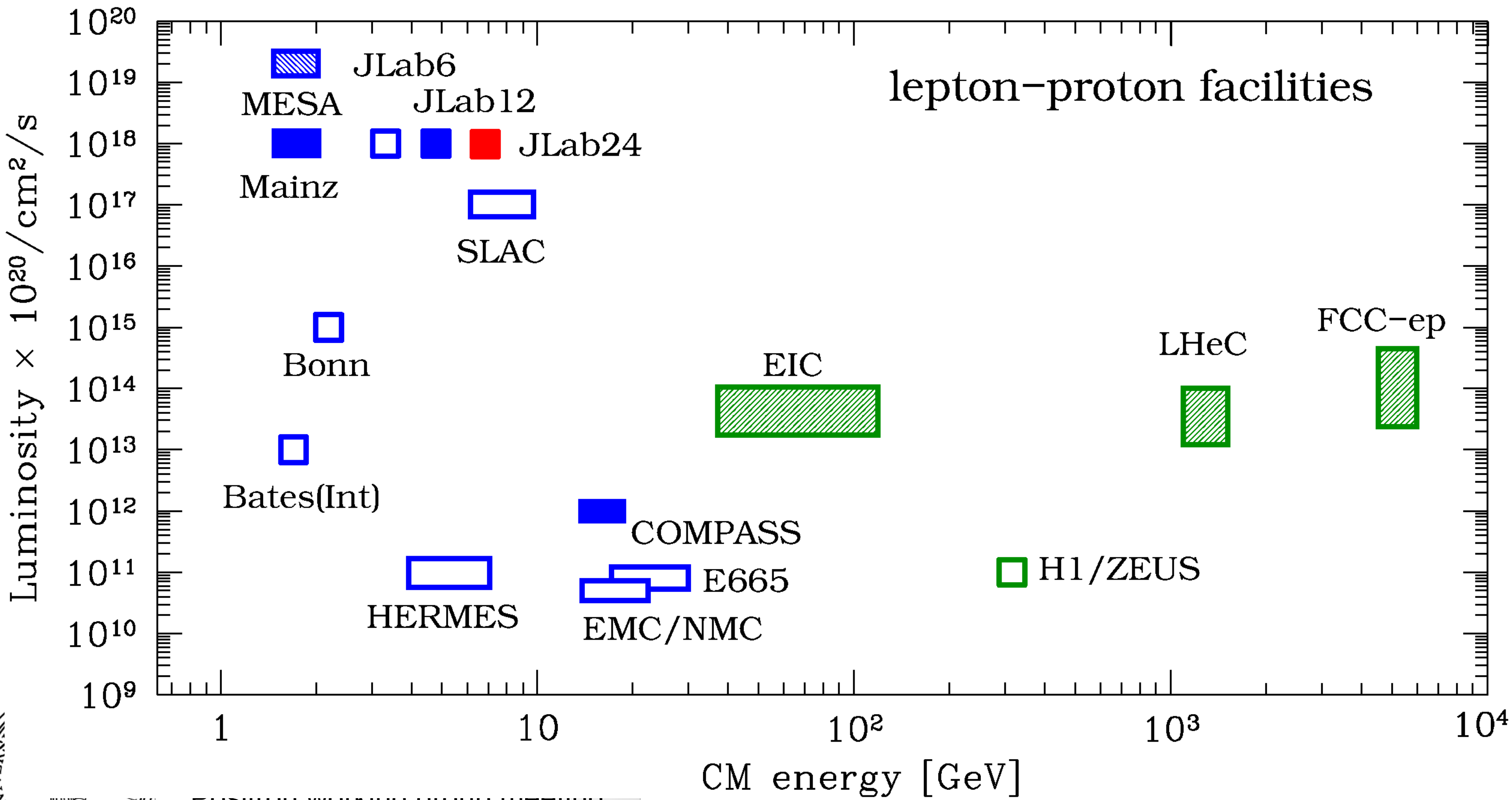
$q_{\text{sea}} = \bar{q}_{\text{sea}}$



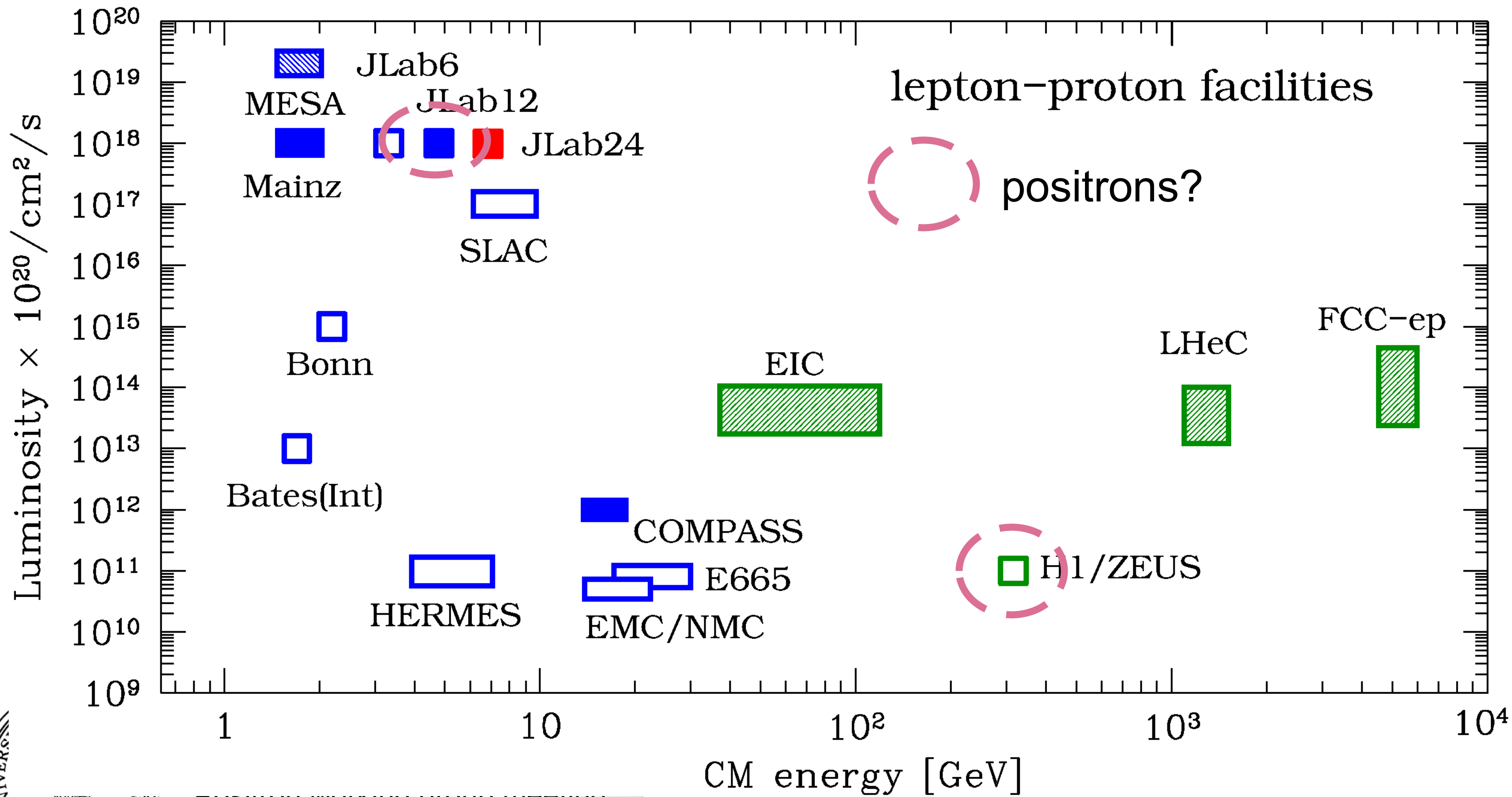
By measuring $A^{e+e-}_{p,d}$ we can access $F_3^{\gamma Z}(x, Q^2)$

(in a similar manner, PV with hadron spin flip can access new $g_{4,5}^{\gamma Z}$ functions)

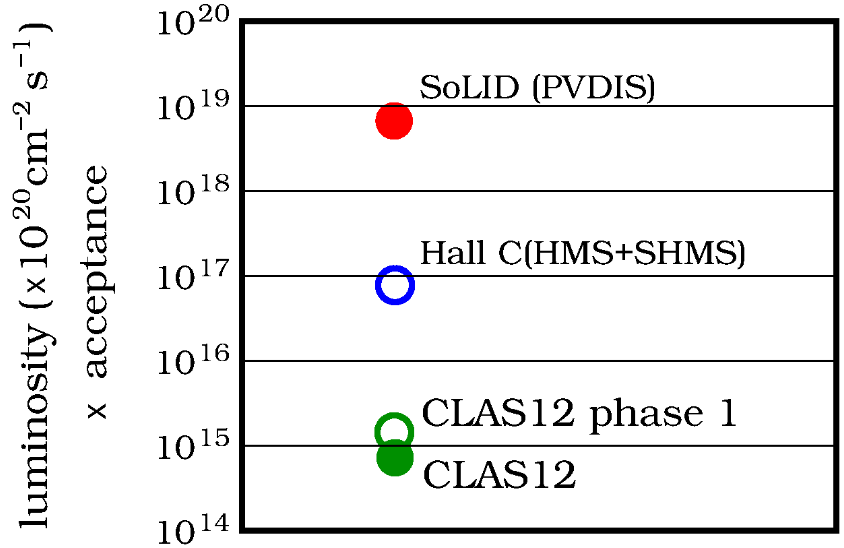
Designing the Experiment

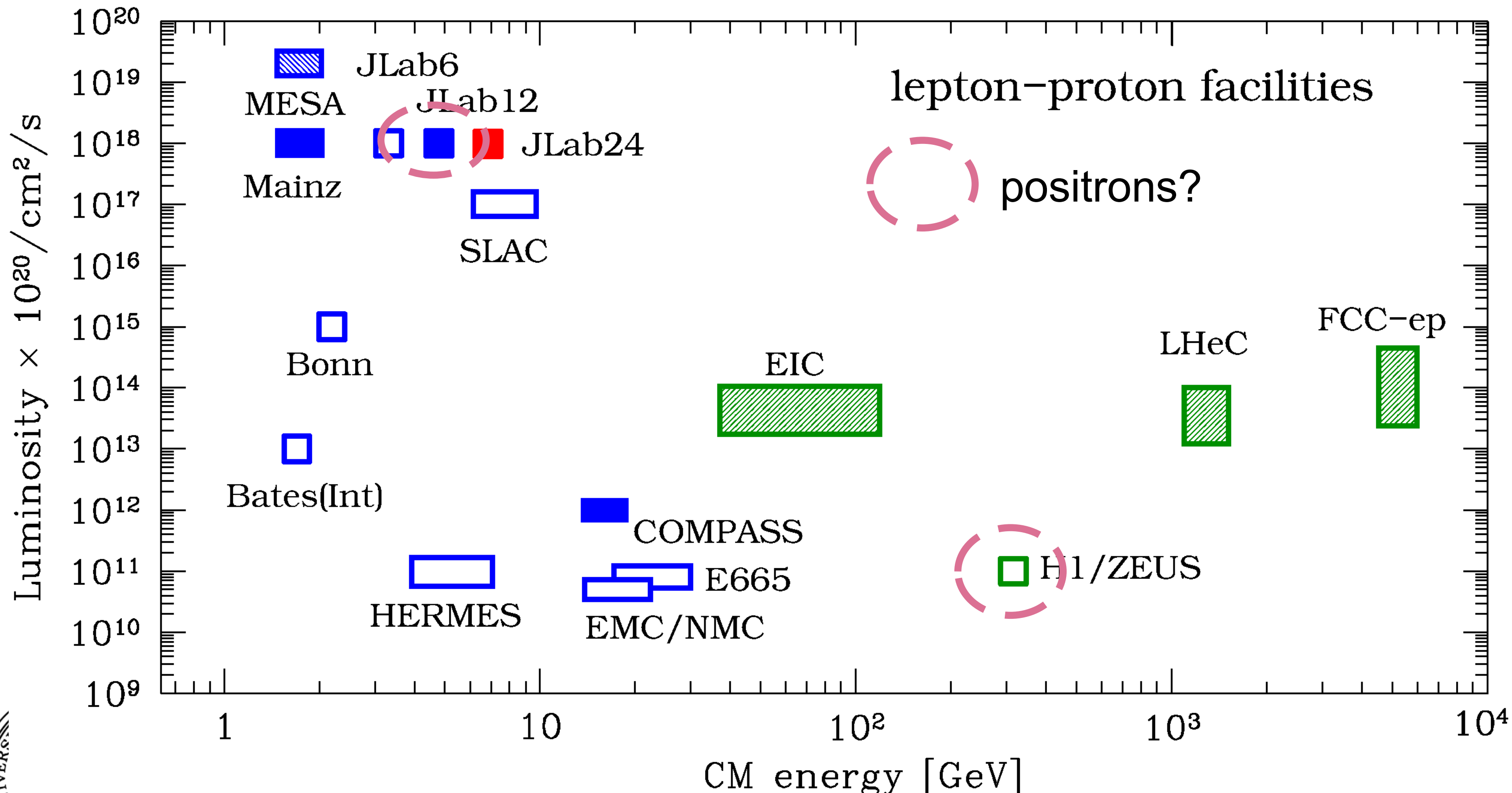


Designing the Experiment



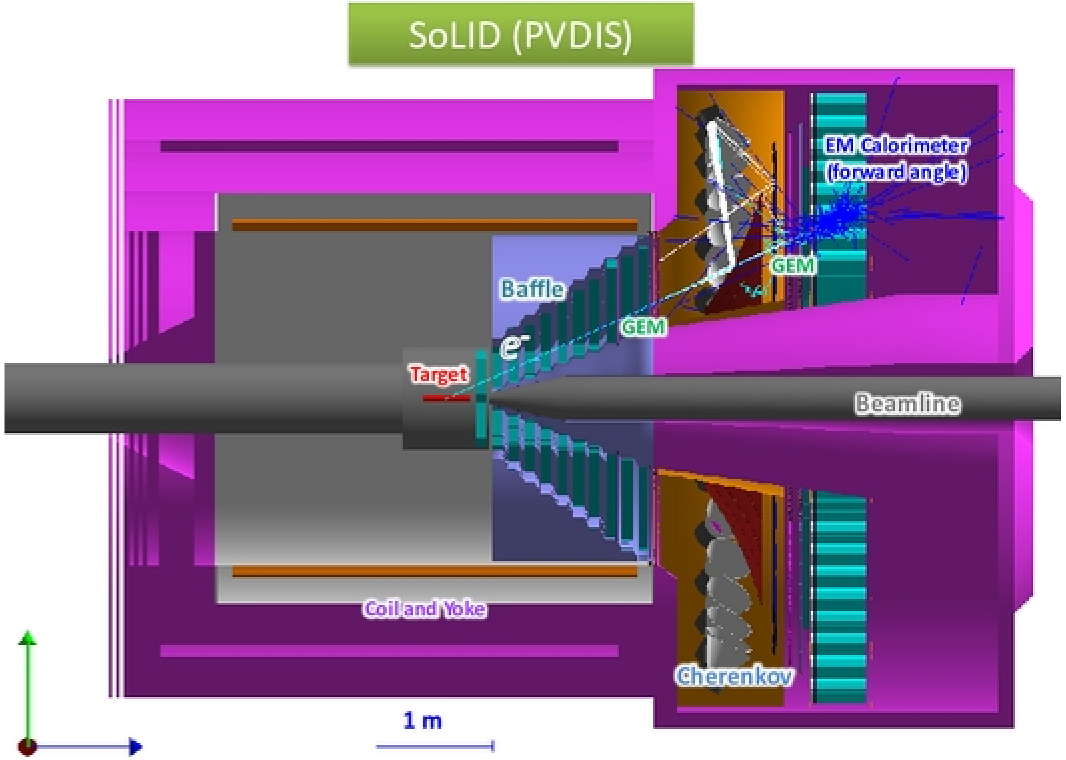
Designing the Experiment



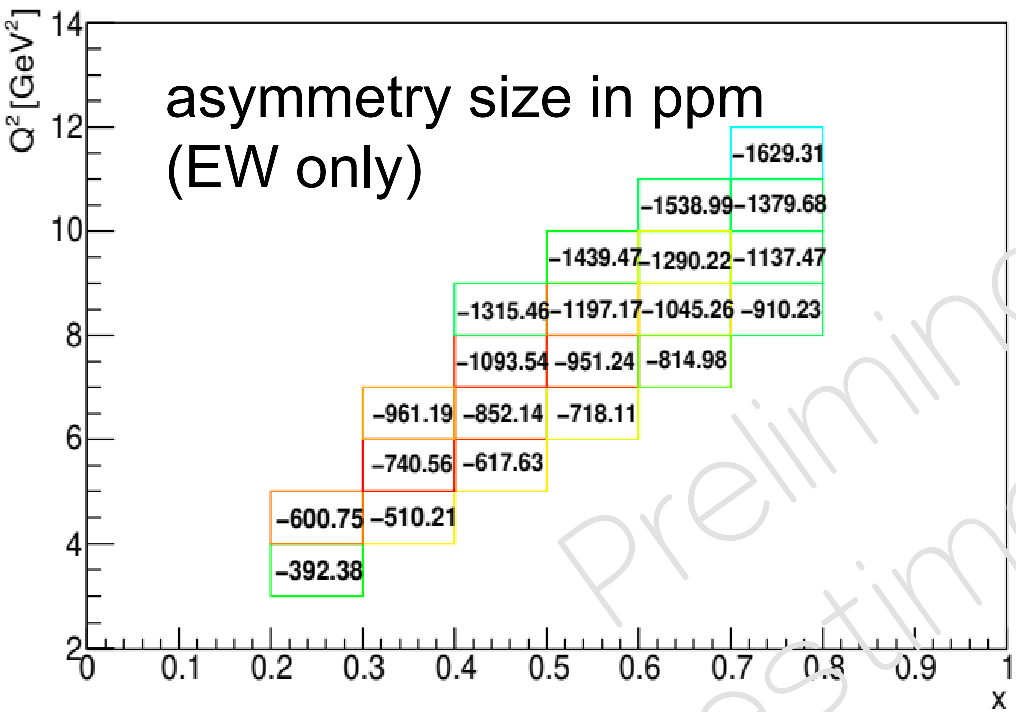


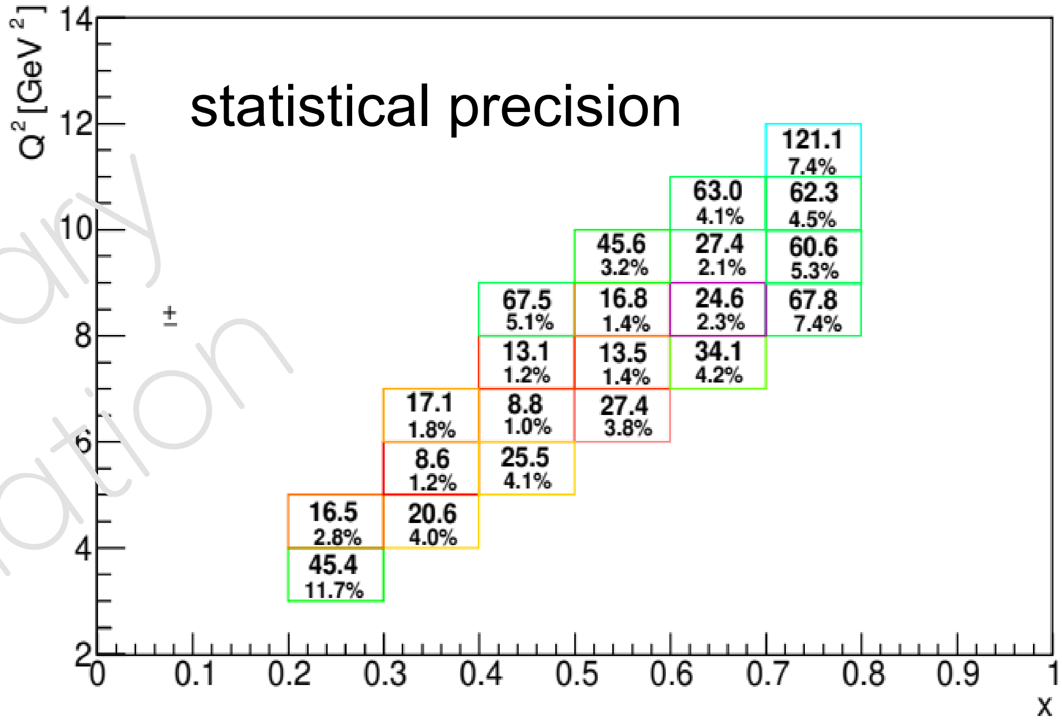
Designing the Experiment

SoLID PVDIS configuration + 40cm LD2
PEPPo: 3uA unpolarized beam
Reverse magnet polarity of SoLID for positron detection



What can we do with 80 days of 3uA beam on a 40cm LD2 target? (in absence of all challenges):

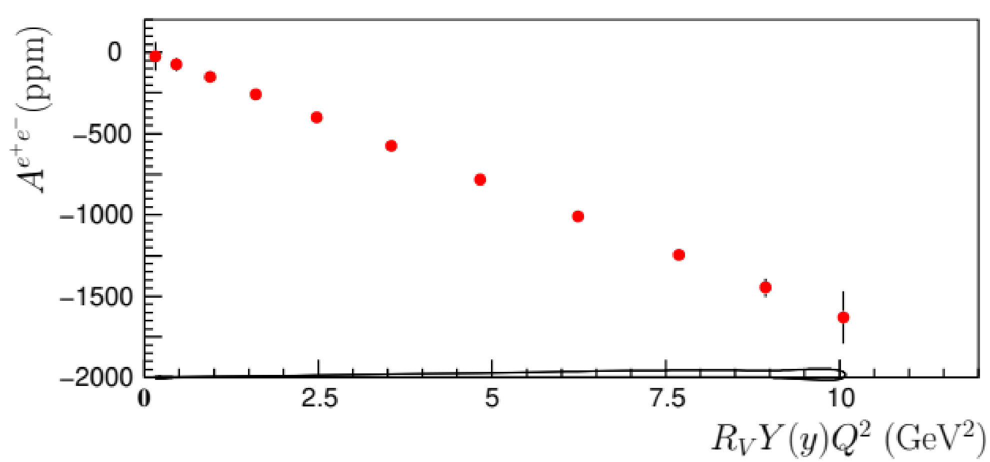




if we consider only statistics and assume A=0 at Q^2=0:

$$A_d^{e^+ \cdot e^-} = -(108\,ppm)\, Q^2 Y\, R_V \left(2C_{3u} - C_{3d}\right)$$

$$\rightarrow 1.5 \pm 0.007$$



Designing the Experiment

SoLID PVDIS configuration + 40cm LD2
PEPPo: 3uA unpolarized beam
Reverse magnet polarity of SoLID for positron detection

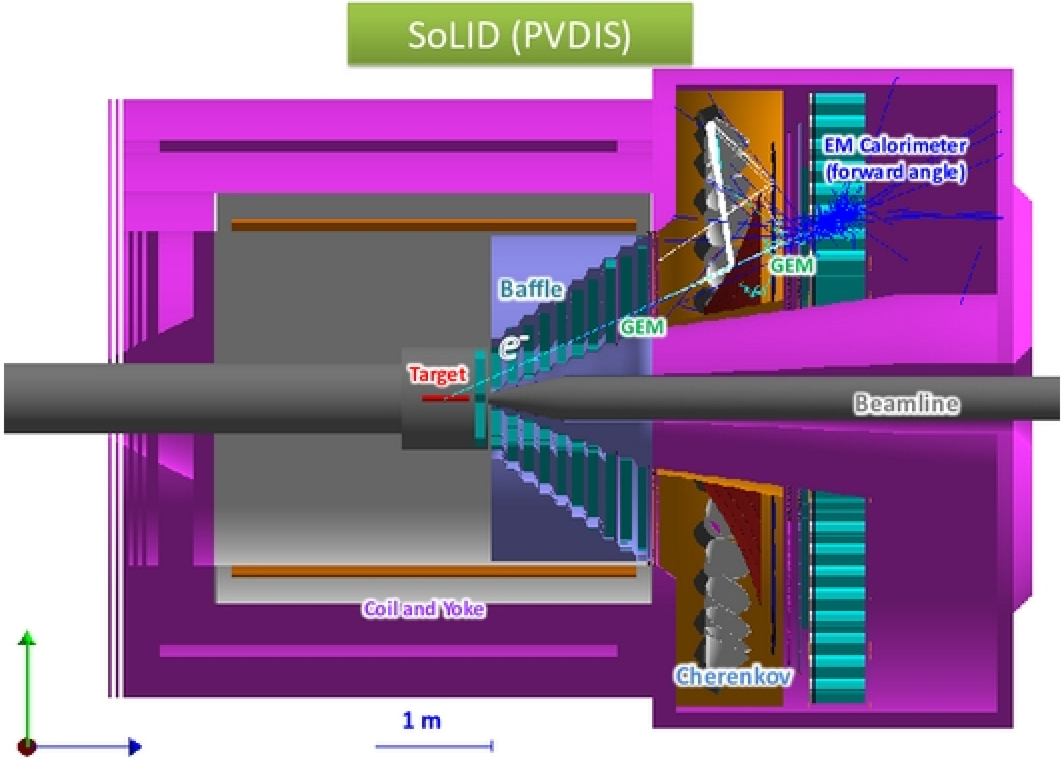
However, flipping e- vs. e+ beam is unlike PVES (30Hz spin flip + Parity DAQ)

Experimental challenges:

- beam energy difference
- beam position difference
- charged pion background
- pair production background
- magnet and detector stability

Theoretical challenges:

- QED higher order effect (no prior precision measurement of e+e- asymmetry in DIS, HERA, SLAC)



All Possible Contributions to the Measured Asymmetry

- slow drift in BCM → (unknown) luminosity difference $\boxed{\Delta\,\mathrm{Lumi}}$
- possible difference in Ebeam ("standard" Hall A → 5x10^{-4}) → can calculate effect $\boxed{\Delta A_{E_b,max}}$
- possible difference in magnet strength (E') → has a plan to control this to <1x10^{-5} → can calculate effect $\boxed{\Delta A_{E',max}}$
- background subtraction → bin by bin

- QED higher order contributions: used Djangoh generator to calculate, proof-of-principle results exist (summer student working on improvement): $\boxed{\Delta A_{QED}}$;
- Coulomb effect: follow Aste et al. https://arxiv.org/abs/nucl-th/0502074 (update from proposal):

Deuteron RMS radius: 2.1421 fm (https://www-nds.iaea.org/ardii) → $R_{eff}=\sqrt{\frac{5}{3}R^2_{rms}}$

→ $V_0=\frac{3}{2}\frac{\alpha\hbar Z}{R_{eff}}$ → $V_{eff}=(0.775\pm0.025)V_0$ and $\text{focusing factor (ff)}=\frac{E_b+V_{eff}}{E_b}$

→ $\sigma_{Coulomb}(E,E',\theta)=\sigma_{Born}(E+V_{eff},E'+V_{eff},\theta)*\mathrm{ff}^2$ – can calculate $\boxed{\Delta A_{Coulomb}}$

- Higher twist is unknown for $F_3^{\gamma Z}(x,Q^2)$, calculated using CJ15's H_2 calculated for SoLID kinematics $\boxed{\Delta A_{CJ15}}$

Experimental Challenges

luminosity difference up to 1% (scaled by 1/10 in the plot) →

Δ Lumi

Eb difference up to 5×10^{-4}

$\Delta A_{E_b,max}$

E' difference up to 1×10^{-5}

$\Delta A_{E',max}$

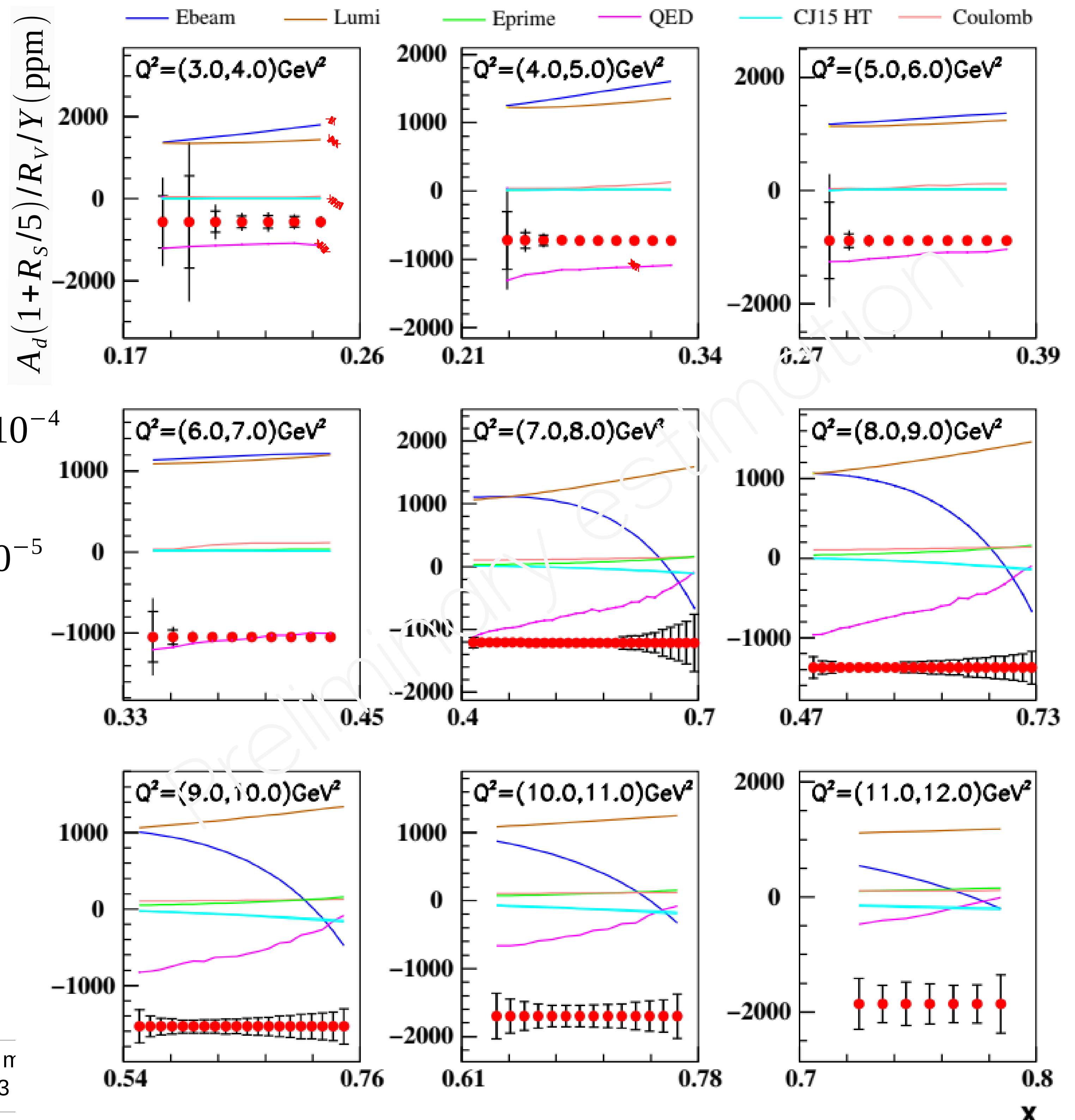
Coulomb correction

$\Delta A_{Coulomb}$

QED higher order (scaled by 1/5) →

ΔA_{QED}

CJ15 HT: ΔA_{CJ15}



Generating Pseudo Data and Apply Multi-Parameter Fit

- For each set of pseudo data (each experiment), initialize random “pre” factors for lumi, Eb, and E’: $d_0(\text{lumi}) \in (-1\%, 1\%), d_1, d_2 \in (-1, 1)$ that follow normal distribution;
- Calculate effect in each (x,Q2) bin the statistical uncertainty (using rates), and the expected maximum effect of lumi, Eb (using 5×10^{-4}), E’ (using 1×10^{-5}), and add background effect:

$$\Delta A_{stat}(x, Q^2), \quad d_0(\text{lumi}), \quad \Delta A_{Eb,\max}(x, Q^2), \quad \Delta A_{E',\max}(x, Q^2)$$

- Produce pseudo data in each fine (x,Q^2) bin, with statistical fluctuation, and add in effect of lumi, Eb, Ep:

$$\boxed{A_{\text{data}}(x, Q^2) = A_{SM} + d_{stat}\,\Delta A_{stat+bg} + d_0 + d_1\,\Delta A_{Eb} + d_2\,\Delta A_{E'}}$$

- Fit (analyze) all pseudo data points using

$$\boxed{A_{\text{data}}(x, Q^2) = p_0 A_{SM}/1.5 + p_{\text{lumi}} + p_1\,\Delta A_{Eb} + p_2\,\Delta A_{E'}} \qquad \boxed{p_0 \rightarrow (2C_{3u} - C_{3d})}$$

fitting pseudo data with lumi (“lumi fit”): $\boxed{\Delta p_0 = \pm 0.032}$

including also Eb factor (“2exp fit”): $\boxed{\Delta p_0 = \pm 0.038}$

including also E’ factor (“3exp fit”): $\boxed{\Delta p_0 = \pm 0.065}$ → Controlling E’ to <10^{-5} desired

- Repeat for 1000 (or 3000) times with random QED+HT, and plot the fitted p_0:

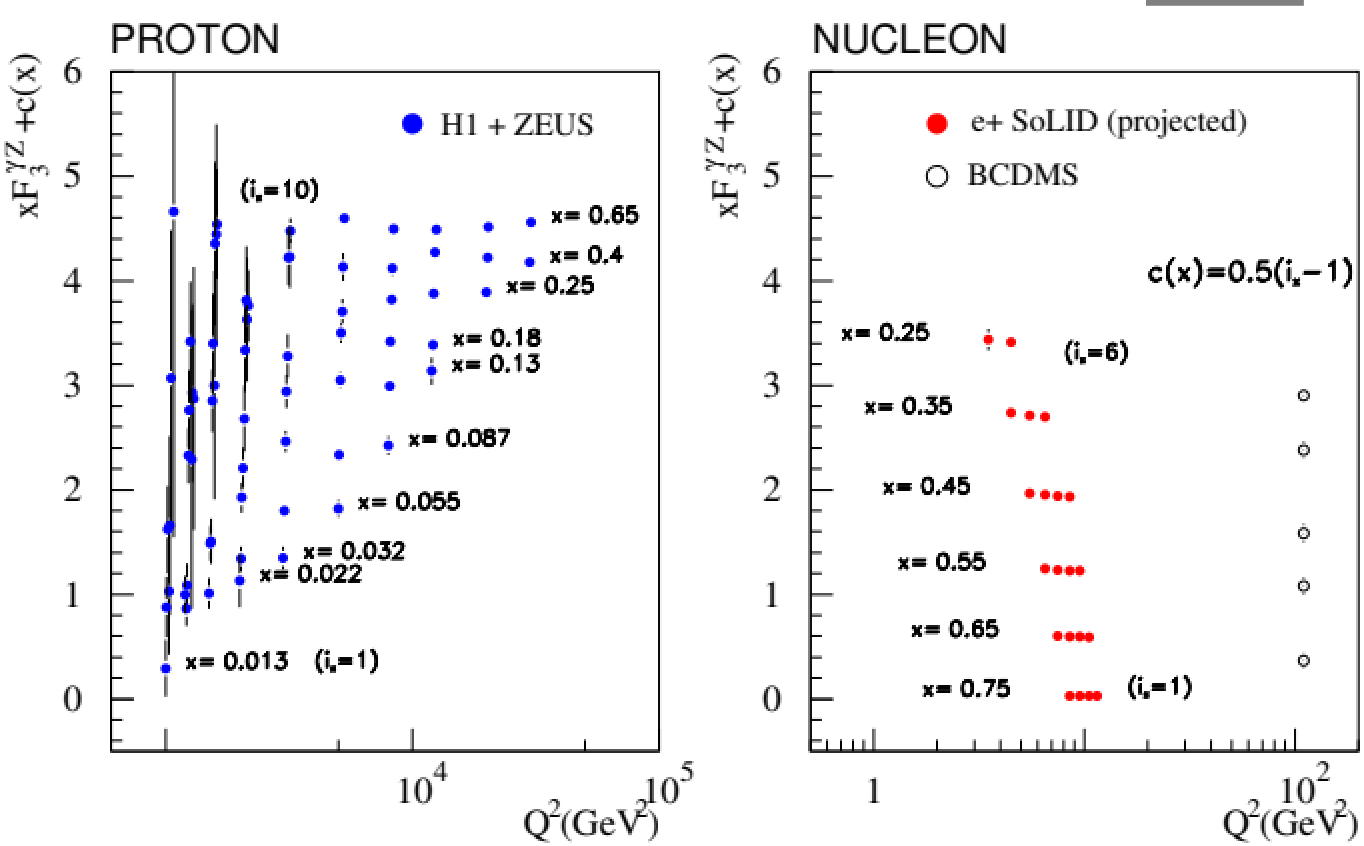
$$\boxed{\Delta(2C_{3u} - C_{3d})_{\text{total}} = \pm 0.053(\text{exp}) \pm 0.009(1\%\ \text{QED}) + 0.000 - 0.035(\text{HT, CJ15}) \approx \pm 0.060}$$

PR12-21-006 Lepton Charge Asymmetry

- 104 PAC days
- positron beam 3uA unpolarized
- beam control (1E-4 beam energy, ? beam position, “fast switch”)

$$\Delta\left(2C_{3u}-C_{3d}\right)_{\text{total}}=\pm 0.053\left(\text{exp}\right)\pm 0.009\left(1\%\ \text{QED}\right)$$
$$+0.000-0.035\left(\text{HT, CJ15}\right)\approx\pm 0.060$$

(4%)



PAC49 report:

Issues: The PAC is pleased to see such an interesting and far-reaching proposal. … ...At the same time, the requirements on the accelerator and theory are both daunting.

Summary: … … leads us to defer the proposal in its present form.

Summary

– By comparing e- vs. e+ DIS cross section, we can form lepton-charge asymmetry that is directly proportional to a new set of eq EW NC coupling: C_{3q} or g_{AA}.

– So far, challenges in both experimental and theoretical systematic effects are both daunting and require further work to make the measurement compelling.

→ charged pion background, tracking efficiency/accuracy

→ beam position control?

– A phased-approach can also be considered: non-EW physics, TPE in DIS, then EW physics

Backup

Summary of Challenges and Why They Exist?

– With a positron beam, the best physics impact comes from comparison between e+ and e- scattering, rather than measuring the same observable (e.g. Apv) as electrons

– If positron vs. electron comparison is our goal, then all systematic effect related to the beam need to be controlled to high precision

– Frequent ("weekly") and fast switch between e+ and e- beams is required to control differences in beam and run conditions → impact on positron beam design.

– Measurements where signal is tiny (EW physics) will be extremely difficult

– Particle background effects on the detector, trigger, and DAQ system.

– There is no well established calculation for TPE (QED NLO) in DIS. All previous (SLAC) data indicated zero but with poor precision;

– HERA data provided only slight constraint on QED NLO in DIS

– We could consider a "phase" approach: study DIS TPE first, then EW physics

Past Experiment – BCDMS

1983 CERN, using polarized μ+ vs. μ- beams:

$$2\,C_{3u}^{\mu q} - C_{3d}^{\mu q} = 1.57 \pm 0.38$$

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

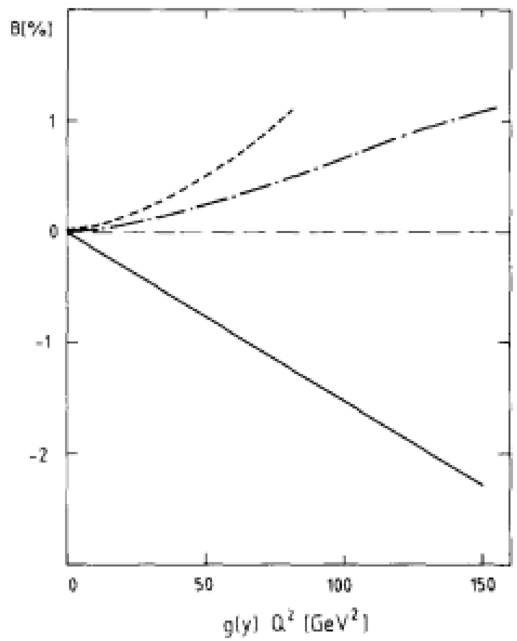


Fig. 2. The B asymmetry from $\gamma - Z^0$ interference to first order, calculated for a polarization $\lambda = 0.81$ and $\sin^2\theta_W = 0.23$ (solid line), and the asymmetry expected from higher order electromagnetic processes at beam energies of 120 GeV (dashed line) and 200 GeV (dashed–dotted line).

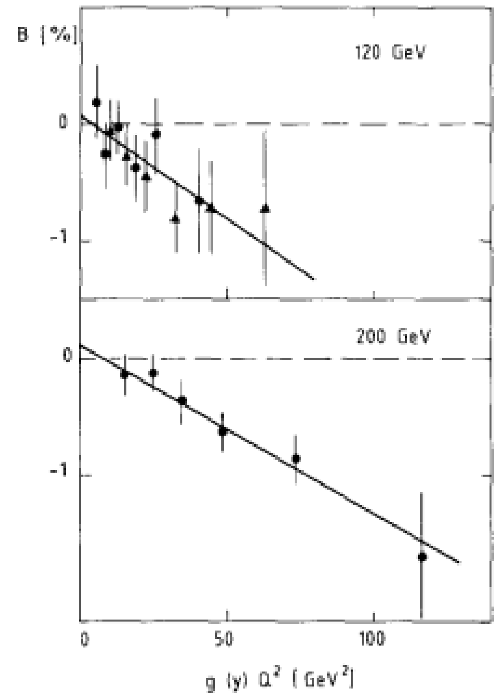


Fig. 3. The measured B asymmetry after radiative corrections at 120 GeV and 200 GeV beam energy versus $g(y)Q^2 = Q^2 \times [1-(1-y)^2]/[1+(1-y)^2]$ [eq. (3)]. For the 120 GeV data, circles represent data with $Q^2 > 15$ GeV. Solid lines are straight line fits to the data.

netic and weak-electromagnetic effects according to ref. [6]; the magnitude of these corrections is shown

a measurement for the electron is highly desired

Experimental Challenges

QED higher order (scaled by 1/5) → ΔA_{QED}