Electroweak Physics with SoLID and a future positron beam at JLab

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

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

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

May 24, 2021

(pending approval from JLab Hall A and SoLID Collaborations)
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

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

\[ Q^2 \ll M_Z^2 \]

\[ VV \text{ (identical to } \gamma) \quad AV, VA \text{ (parity-violating) } \quad AA \]

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

\[ C_{1d} = 2 g_A^e g_V^d = \frac{1}{2} - \frac{2}{3} \sin^2(\theta_W) \quad C_{2d} = 2 g_V^e g_A^d = \frac{1}{2} - 2 \sin^2(\theta_W) \quad C_{3d} = -2 g_A^e g_A^d = -\frac{1}{2} \]

- 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

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

https://arxiv.org/abs/2103.12555
In the Parton Model (low energy)

\[
A_{RL}^{e^\pm} = \frac{\sigma_R^{e^\pm} - \sigma_L^{e^\pm}}{\sigma_R^{e^\pm} + \sigma_L^{e^\pm}}, \quad (A_{RL}^{e^\pm} = - A_{LR}^{e^\pm})
\]

beam polarization

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

\[
Y(y) = \frac{1-(1-y)^2}{1+|1-y|^2} \quad R_V(x) = \frac{u_x |x| + d_x |x|}{u_x |x| + \bar{u} |x| + d_x |x| + \bar{d} |x|}
\]

(indicates spin flip of quarks)
In the Parton Model (low energy)

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

\[A_{RL}^{e^+} = -A_{LR}^{e^-}\]

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

\[A_{RL}^{e^-e^+} \neq -A_{LR}^{e^-e^+}\]

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

\[A_{RR}^{e^+e^-} \neq -A_{LL}^{e^+e^-}\]

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

\[A_{d}^{e^+e^-} = -(108 \text{ ppm})Q^2 Y(y) R_V(x) |2C_{3u} - C_{3d}| \]

Beam polarization

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

\[
R_V(x) = \frac{u_v x + d_v x}{u \bar{x} + \bar{u} x + d \bar{x} + \bar{d} x}
\]

(indicates spin flip of quarks)

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

(flip |\lambda| for LR)

“B” in CERN measurement

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

(flip |\lambda| for LL)

(no polarization needed!)

“direct” access to \(2C_{3u} - C_{3d}\)
e^+e^- for Structure Function Study

Approximately:

\[ A_{unpol}^{e^+e^-} = \frac{G_F Q^2}{2 \sqrt{2} \pi} \alpha \left( \frac{g_A^e}{2} \right) Y (y) \frac{F_3^{YZ}}{F_1^y} \]

(in Apv, \( F_3^{YZ} \) is suppressed by \( g_V^e \))

In the parton model:

\[ F_1^y (x, Q^2) = \frac{1}{2} \sum Q_q^2 [q + \bar{q}] \]

\[ F_3^{YZ} (x, Q^2) = 2 \sum g_A^q [q - \bar{q}] \]

Low x HERA data pose question on \( q_{sea} = \bar{q}_{sea} \)

By measuring \( A_{p,d}^{e^+e^-} \) we can access \( F_3^{YZ} (x, Q^2) \)
Designing the Experiment
Designing the Experiment
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- SoLID (PVDIS)
- Hall C (HMS+SHMS)
- CLAS12 phase 1
- CLAS12

- lepton-proton facilities
- positrons?

- JLab6
- JLab12
- JLab24
- MESA
- Mainz
- SLAC
- Bonn
- Bates(Int)
- EIC
- LHeC
- FCC-ep
- HERMES
- COMPASS
- E665
- EMC/NMC
- H1/ZEUS
Designing the Experiment

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

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

$$A_{d}^{e^+e^-} = -(108 \text{ ppm}) Q^2 Y R_Y \left(2C_{3u} - C_{3d}\right)$$

$$\rightarrow 1.5 \pm 0.007$$
Experimental challenges:

beam energy difference
beam luminosity difference
beam position difference
charged pion background
pair production background
magnet and detector stability
Theoretical challenges: – higher-order QED corrections

Experimental challenges:

beam energy difference
beam luminosity difference
beam position difference
charged pion background
pair production background
magnet and detector stability
PR12-21-006 Lepton Charge Asymmetry

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

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

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.
– A phased-approach can also be considered: study TPE in DIS using 11 GeV and EW physics with a 22 GeV (e+) beam.
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
What can we do with 80 days of 3uA beam on a 40cm LD2 target? (in absence of all challenges):

asymmetry size in ppm (EW only)

statistical precision

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

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

$\rightarrow 1.5 \pm 0.007$
Past Experiment – BCDMS

1983 CERN, using polarized $\mu^+$ vs. $\mu^-$ beams:

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

a measurement for the electron is highly desired
Experimental Challenges

QED higher order (scaled by $1/5$) $\rightarrow \Delta A_{QED}$