Weak Neutral Current Studies with Positrons

Seamus Riordan
seamus@anl.gov

September 14, 2017
Weak force couplings provide unique mode to study nature

Charged current (e.g. $\beta$ decay) maximally violating, but neutral current mixed by weak mixing angle $\sin^2 \theta_W$

Arises in low $Q^2$ $e^-$ scattering as interference between $\gamma$ and $Z$

Basic object of study is PV asymmetry

$$\frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = A_{PV} = \frac{\gamma^* \gamma^*}{2} \sim \frac{G_F Q^2}{\sqrt{2\pi\alpha}} \times \ldots$$

$$= 10^{-6} \sim 10^{-3}$$
Neutral Current Structure and Positrons

- Standard $e^-$ parity violating asymmetry typically has two terms

$$A = \frac{R - L}{R + L} \sim \frac{G_F Q^2}{\sqrt{2\pi\alpha}} \left[ D_f(\theta)g_A^e g_V^\text{target} + D_b(\theta)g_V^e g_A^\text{target} \right]$$

$$g_A = T_3, \quad g_V = T_3 - 2Q \sin^2 \theta_W$$

$$T_3 \sim \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L, \begin{pmatrix} u \\ d \end{pmatrix}_L,$$

- Second term is typically harder to get to kinematically
  - Requires kinematic separation
  - $g_V^e$ is $\sim 0.1$, $g_V^q$ larger

- Axial terms under C effectively $g_A \rightarrow -g_A$
Neutral Current Structure and Positrons (II)

- $e^+(R/L) - e^-(L/R)$ asymmetry offers unique interesting combination

$$\Delta = (\pm g^e_V + g^e_A) G^\text{target}_A(x, Q^2) \times \ldots$$

- Axial-axial coupling unique and not suppressed by $1 - 4 \sin^2 \theta_W$!
- Don’t actually need spin for separation - relative intensity control must be much better than asymmetry
- Axial term of targets has interesting physics opportunities
  - DIS - $C_{3q}$ couplings
  - $q - \bar{q}$ pdfs
  - $ep$ - Direct access to axial form factor
- Other opportunities
  - Sign flip in EM higher order effects
  - s-channel studies
Parity experiments are high current - going to assume 6 $\mu$A

Requires exquisite control of systematics
  - Rapid flipping of states!
  - Beam properties at injector
  - High precision polarimetry
  - Control and measurement of beam intensity, energy, position

Largely going to ignore these issues
Elastic ep

\[ A = \left[ -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \left[ \frac{\epsilon G^\gamma_E G^Z_E + \tau G^\gamma_M G^Z_M + 2g^e \epsilon' G^\gamma_M G^Z_A}{\epsilon (G^\gamma_E)^2 + \tau (G^\gamma_M)^2} \right] \]

\[ \epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1}; \quad \epsilon' = \sqrt{\tau(1 + \tau)(1 - \epsilon^2)}; \quad \tau = \frac{Q^2}{4M^2} \]

\[ G^{pZ}_E = (1 - 4\sin^2 \theta_W) G^{p\gamma}_E - G^{n\gamma}_E - G^{s\gamma}_E \]

- G0 covered \( Q^2 \) 0.1-1 GeV\(^2\) at various
- Two backwards angle runs on LH\(_2\) and QE LD\(_2\)
- Extracted \( G_A \) with considerable uncertainty
  Axial \( \sim 20\% \) contribution to proton asymmetry
Axial FF

- Axial form factor measured in $\beta$ decay only isovector component with $n \rightarrow p$ by SU(3)
- Related to spin structure and DIS

$$\Gamma_1^p = \frac{1}{2} \int_0^1 \sum e_i^2 \Delta q_i(x) dx \sim \frac{1}{12} g_A^{(3)} + \frac{1}{36} g_A^{(8)} + \frac{1}{9} g_A^{(0)} + ...$$

- Proton neutral current $G_A$ includes isoscalar components (i.e. strange quarks and also radiative components)

$$G_A^p(Q^2 = 0) = g_A^{(3)} \left( 1 + R_A^{T=1} \right) + \frac{3F - D}{2} R_A^{T=0} + \Delta s \left( 1 + R_A^{(0)} \right)$$

$$\Delta s = g_A^{(8)} - g_A^{(0)}$$
Radiative Corrections

- Radiative corrections to Axial FF not well known, difficult to calculate 

\[
R_A^{T=1} = -0.258(0.34) \quad R_A^{T=0} = -0.239(0.2) \quad R_A^0 = -0.551
\]

- Typically only small suppressed component in forward experiments

- In positron measurement targeting axial FF, on the order 10%

\[
A^{e^+ - e^-} = \frac{G_F Q^2}{2\pi \alpha \sqrt{2}} g_A^e \frac{G_A^Z G_M^\gamma}{\epsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}
\]

- Totally overwhelmed by $\gamma\gamma\gamma$ terms

- 6 $\mu$A, trying to get 10% measurement of $G_A^Z$, similar G0 kinematic run time ignoring 2$\gamma$...

- $A_{PV}$ radiative corrections (e.g. $\gamma - Z$ box diagrams) $V$ and $A$ corrections have positron sign flip in each single measurement not enough to constrain (Afanasev, Carlson PRL 94 212301 (2005))
Radiative Corrections

- Exception for spinless targets → no axial current
- Sensitive to box of extra photon

\[ A_{\text{extra photon}} = A_{PV}^{e+} + A_{PV}^{e-} \]

Afanasev, Carlson PRL 94 212301 (2005)
PVDIS - Deep Inelastic Scattering

- PVDIS gives access to underlying partonic structure
- Rate at high $Q^2 \rightarrow$ relatively larger statistics and asymmetry
- $A_e V_q \ (C_{1q})$ and $V_e A_q \ (C_{2q})$ effective couplings
- Excellent combination to test new physics and QCD nucleon/nuclear structure!

\[
A_{PV} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ a_1(x) + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3(x) \right], \quad y = 1 - \frac{E'}{E}
\]
\[
a_1(x) = 2 \sum \frac{C_{1q} e_q (q + \bar{q})}{\sum e_q^2 (q + \bar{q})}, \quad a_3(x) = 2 \sum \frac{C_{2q} e_q (q - \bar{q})}{\sum e_q^2 (q + \bar{q})}
\]

\[
C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W = -0.19 \quad C_{2u} = -\frac{1}{2} + 2 \sin^2 \theta_W = -0.03
\]
\[
C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W = 0.34 \quad C_{2d} = \frac{1}{2} - 2 \sin^2 \theta_W = 0.03
\]
New large installation project, over 250 international collaborators!

Broad experimental including PVDIS, SIDIS, $J/\psi$, and more!

$Q^2 \sim 2 - 8 \text{GeV}^2$, $x = 0.2 - 1$, $dA_{PV}/A < 1\%$

Based around CLEO2 magnet - now at JLab
SoLID - PVDIS SM and Nucleon Properties

- 60 $\mu$A on 40 cm LH$_2$ or LD$_2$ target
- Errors for 120 days 11 GeV LD$_2$ give sub 1% in many bins
- Constraints on $\Lambda \sim 10$-20 TeV
Axial-Axial in DIS has effective couplings $C_{3q} = \pm \frac{1}{2}$

$$A_{e^+(R/L)-e^-(L/R)} = \frac{G_F Q^2}{4\sqrt{2}\alpha\pi} \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \sum (C_{2q} \pm C_{3q}) e_q(q - \bar{q}) \sum e^2_q(q + \bar{q})$$

- Only measured once at CERN with $\mu^+$ and $\mu^-$ on C to $\sim25\%$ level
- To get few $\%$ measurement of $2C_{3u} - C_{3d}$ on LD$_2$, 30 days 6 $\mu$A with SoLID
- Asymmetries on the order of 100 s ppm - beam quality systematics are less stringent
EIC - Additional sea quark information

- $F_3$ is $q - \bar{q}$ PDFs $\rightarrow$ valence/sea quark info
- Also has analogous polarized nucleus version
- Complementary to charge current processes which is flavor changing
- Also previous studied at HERA

Zhao, Deshpande, Huang, Kumar, SPR EPJ A (2017) 53: 55
Zhao, Deshpande, Huang, Kumar, SPR EPJ A (2017) 53: 55

- $F_3$ is $q - \bar{q}$ PDFs → valence/sea quark info
- Also has analogous polarized nucleus version
- Complementary to charge current processes which is flavor changing
- Also previous studied at HERA
sin²θ_W to new world leading precision

11 GeV beam on 150 cm LH₂ target with accepted θ = 6 – 17 mrad

A_{PV} = 35 ppb to 2.1%

\[ A_{ee} = m_e E \frac{G_F}{\sqrt{2 \pi \alpha}} \frac{4 \sin^2 \theta_{\text{CoM}}}{(3 + \cos^2 \theta_{\text{CoM}})^2} \left( 1 - 4 \sin^2 \theta_W \right) \]

Symmetric in electrons - already have access to product \( g_A^e g_V^e \) so probably not a lot interesting
$e^+ e^- \rightarrow f \bar{f}$?

Other couplings to fermions not as well measured!

- Interesting for proton radius puzzle? (maybe in loops?)
- Need $4m_{\mu}^2 < s = 2m_e E \sim 43 \text{ GeV}$ $e^+$ to do this on fixed target...
- Statistics for colliders off $Z$ resonance too challenging
$e^+ e^- \rightarrow f \bar{f}$?

Other couplings to fermions not as well measured!

- Interesting for proton radius puzzle? (maybe in loops?)
- Need $4m_{\mu}^2 < s = 2m_e E \sim 43 \text{ GeV}$ $e^+$ to do this on fixed target...
- Statistics for colliders off $Z$ resonance too challenging
**PREX and CREX - Nuclear Neutron Skin Measurements**

\[ Q^p_{\text{weak}} \sim 0.1 \quad Q^n_{\text{weak}} \sim -1 \]

- \( Z \) primarily couples to neutron distributions - otherwise elastic FF measurement
- Neutron skin \( \equiv \sqrt{\langle R^2_n \rangle} - \sqrt{\langle R^2_p \rangle} \)
- PREX-I completed in 2010 (1.1 GeV, 5\(^\circ\))
- Confirmed existence of \(^{208}\)Pb skin at 95% CL measuring 0.7 ppm asymmetry

Coulomb corrections critical!
electron minima show up at smaller $q$ than positron
Effect is very small!

Breton et al, PRL 66 (1991) 572
- Coulomb corrections critical!
- electron minima show up at smaller $q$ than positron
- Effect is very small!

\[ A_{\nu} = \frac{G_F Q^2}{4\pi \alpha \sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)} \]

Donnelly, Dubach & Sick (1988)
Horowitz, Michaels and Souder (2001)

Special thanks to C. Horowitz
Transverse spin asymmetry has small $\sim 10^{-5}$ asymmetries

Only $2\gamma$ contributions by $T$

Lead surprisingly small
Calculations are dispersive only - Coulomb not included
Positron would give extra information - few days of 6 $\mu$A data?
Neutral Currents with $e^-$ and $e^+$ give access to axial-axial couplings

Axial properties of targets are often suppressed for JLab kinematics and are more difficult to measure but have interesting unique physics

Low positron current and worse beam currents make the feasibility of such studies very challenging

DIS with SoLID could constrain $C_{3q}$ couplings and EIC could offer unique channel for sea quarks
BACKUP
10. Electroweak model and constraints on new physics

Figure 10.2: Scale dependence of the weak mixing angle defined in the MS scheme [122] (for the scale dependence of the weak mixing angle defined in a mass-dependent renormalization scheme, see Ref. 123). The minimum of the curve corresponds to $\theta = M_W$, below which we switch to an effective theory with the $W^\pm$ bosons integrated out, and where the $\beta$-function for the weak mixing angle changes sign. At the location of the $W$ boson mass and each fermion mass there are also discontinuities arising from scheme dependent matching terms which are necessary to ensure that the various effective field theories within a given loop order describe the same physics. However, in the MS scheme these are very small numerically and barely visible in the figure provided one decouples quarks at $\theta = \hat{m}_q(\hat{m}_q)$. The width of the curve reflects the theory uncertainty from strong interaction effects which at low energies is at the level of $\pm 7 \times 10^{-5}[122]$. Following the estimate [124] of the typical momentum transfer for parity violation experiments in Cs, the location of the APV data point is given by $\theta = 2.4$ MeV. For NuTeV we display the updated value from Ref. 125 and chose $\theta = \sqrt{20}$ GeV which is about half-way between the averages of $\sqrt{Q^2}$ for $\nu$ and $\bar{\nu}$ interactions at NuTeV. The Tevatron and LHC measurements are strongly dominated by invariant masses of the final state dilepton pair of $O(M_Z)$ and can thus be considered as additional $Z$ pole data points. For clarity we displayed the Tevatron and LHC points horizontally to the left and to the right, respectively.

In a similar experiment and at about the same $Q^2 = 0.025$ GeV$^2$, Qweak at Jefferson Lab [126] will be able to measure the weak charge of the proton (which is proportional to $2g_{eu}AV + g_{ed}AV$) and $\sin^2 \theta_W$ in polarized ep scattering with relative precisions of 4% and 0.3%, respectively. The result based on the collaborations commissioning run [127] and...
Access to Beyond the Standard Model

- Variety of experiments have unique and complementary sensitivity to new physics and complementary systematics
- Search for differences in $\sin^2 \theta_W$
- Probe new large energy scale $\Lambda$ through interference contact interactions
- Complementary to searches at high energy colliders

Variety of experiments have unique and complementary sensitivity to new physics and complementary systematics.

Search for differences in $\sin^2 \theta_W$.

Probe new large energy scale $\Lambda$ through interference contact interactions.

Complementary to searches at high energy colliders.

Figure 10.2: Scale dependence of the weak mixing angle defined in the $\overline{\text{MS}}$ scheme [122] (for the scale dependence of the weak mixing angle defined in a mass-dependent renormalization scheme, see Ref. 123). The minimum of the curve corresponds to $\theta = \frac{M_W}{\sqrt{2}}$, below which we switch to an effective theory with the $W^\pm$ bosons integrated out, and where the $\beta$-function for the weak mixing angle changes sign. At the location of the $W$ boson mass and each fermion mass there are also discontinuities arising from scheme dependent matching terms which are necessary to ensure that the various effective field theories within a given loop order describe the same physics. However, in the $\overline{\text{MS}}$ scheme these are very small numerically and barely visible in the figure provided one decouples quarks at $\theta = \hat{m}_q(\hat{m}_q)$. The width of the curve reflects the theory uncertainty from strong interaction effects which at low energies is at the level of $\pm 7 \times 10^{-5}$ [122]. Following the estimate [124] of the typical momentum transfer for parity violation experiments in Cs, the location of the APV data point is given by $\theta = 2.4 \text{ MeV}$. For NuTeV we display the updated value from Ref. 125 and chose $\theta = \sqrt{20 \text{ GeV}}$ which is about halfway between the averages of $\sqrt{Q^2}$ for $\nu$ and $\bar{\nu}$ interactions at NuTeV. The Tevatron and LHC measurements are strongly dominated by invariant masses of the final state dilepton pair of $O(M_Z)$ and can thus be considered as additional $Z$ pole data points. For clarity we displayed the Tevatron and LHC points horizontally to the left and to the right, respectively.

In a similar experiment and at about the same $Q^2 = 0.025 \text{ GeV}^2$, $Q_{\text{weak}}$ at Jefferson Lab [126] will be able to measure the weak charge of the proton (which is proportional to $2 g^{\text{eu}}_{\text{APV}} + g^{\text{ed}}_{\text{APV}}$) and $\sin^2 \theta_W$ in polarized $ep$ scattering with relative precisions of 4% and 0.3%, respectively. The result based on the collaborations commissioning run [127] and

Few percent sensitivity ↓ several TeV level probe

$\sim \frac{g^2}{\Lambda^2}$