The proton’s weak charge

Workshop on New physics at the low-energy precision frontier

LPT Orsay, September 16–20, 2019
Measurements
  * the past: JLab–Qweak
  * the future: JGU–P2

Higher-order corrections
  * 1-loop radiative corrections
  * the weak mixing angle at low energy
  * form factors
  * the γZ box

Beyond the Standard Model
  * model-independent constraints
  * constraints on simple models

Related experiments
  * other targets
  * other projectiles
  * DIS
  * APV

Conclusions
Measurements
* Tuning in on the Z resonance
  * Leptonic and heavy quark FB asymmetries in $e^+e^-$ annihilation near $s = M_Z^2$
  * Leptonic FB asymmetries in $pp$ ($p\bar{p}$) Drell-Yan in a window around $m_\tau = M_Z$
  * LR asymmetry (SLC) and final state $\tau$ polarization (LEP) and their FB asymmetries

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<th>V scattering</th>
<th>parity violating e(^-) scattering (PVES)</th>
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* tuning in on the $Z$ resonance
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  * LR asymmetry (SLC) and final state $\tau$ polarization (LEP) and their FB asymmetries

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### Weak mixing angle approaches

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Running weak mixing angle

\[
\sin^2 \theta_W(\mu) = \frac{1}{2} \left( 1 + \frac{\alpha_2}{\mu^2} \right)
\]

- **RGE Running**
- **Particle Threshold**
- **Measurements**
- **Proposed**

Ferro-Hernández & JE
arXiv:1712.09146
Weak charge of a nucleus

\[ Q_w(N,Z) \approx -2 (Z g_{AV}^{ep} + N g_{AV}^{en}) \approx Z (1 - 4 \sin^2 \theta_W) - N \]
\[ Q_w(p) \approx -4 g_{AV}^{ep} - 2 g_{AV}^{en} \approx 1 - 4 \sin^2 \theta_W \]
\[ g_{AV}^{ep} = 2 g_{AV}^{eu} + g_{AV}^{ed} \]
\[ g_{AV}^{en} = g_{AV}^{eu} + 2 g_{AV}^{ed} \]

Coherent elastic ν nucleus scattering (CEvNS) \( \sim G_F^2 Q^4 Q_W^2 \)
Parity violating elastic e\(^-\) scattering (PVES) \( \sim G_F Q^2 Q_W \)

special case of proton: \( Z = 1, N = 0 \)

⇒ extra sensitivity to weak mixing angle and new physics

need small \( Q^2 \) to suppress form factor effects

not too small to maintain measurable cross section (asymmetry)
Parity violating asymmetry (Qweak)

after EM radiative corrections and accounting for signal dilutions and false or background process asymmetries

\[ A_{msr} = P_e A_{LR} \]

\[ P_e = 87.66 \pm 1.05 \% \text{ (Run I)} \quad P_e = 88.71 \pm 0.55 \% \text{ (Run II)} \]

\[ A_{LR} = (226.5 \pm 7.3_{\text{stat}} \pm 5.8_{\text{syst}}) \times 10^{-9} \]

\[ y \equiv 1 - E_e'/E_e = 0.0115 \quad (\text{average scattering angle } \theta = 7.9^\circ) \]

\[ O(y^2)\text{-terms} \text{ from vector, strange and axial form factors} \]

\[ \text{for } P2: \quad (35.2 \pm 0.5)\% \quad \text{for scattering angles in the window } \theta = (35 \pm 20)^\circ \quad (\text{average } y = 0.0157) \]
Qweak @ CEBAF (JLab)

hydrogen (completed)

\( E_e = 1149 \text{ MeV} \)

\(|Q| = 158 \text{ MeV} (\theta = 7.9^\circ)\)

\( A_{PV} = 2.3 \times 10^{-7} \)

\( \Delta A_{PV} = \pm 4.1\% \)

\( \Delta Q_W(p) = \pm 6.25\% \)

\( \sin^2 \theta_W = 0.2383 \pm 0.0011 \)

FFs from fit to ep asymmetries

arXiv:1905.08283
Parity Violating e− Scattering (PVES) — Elastic

**Qweak @ CEBAF (JLab)**

hydrogen (completed)

\[ E_e = 1149 \text{ MeV} \]

\[ |Q| = 158 \text{ MeV (θ = 7.9°)} \]

\[ A_{PV} = 2.3 \times 10^{-7} \]

\[ \Delta A_{PV} = \pm 4.1\% \]

\[ \Delta Q_w(p) = \pm 6.25\% \]

(± 5.3% with lattice input)

FFs from fit to ep asymmetries


**Parity Violating $e^-$ Scattering (PVES) — Elastic**

**P2 @ MESA (JGU Mainz)**

hydrogen (CDR)

$E_e = 155$ MeV

$|Q| = 68$ MeV ($\theta = 35^\circ \pm 20^\circ$)

$A_{PV} = 4 \times 10^{-8}$

$\Delta A_{PV} = \pm 1.4\%$

$\Delta Q_W(p) = \pm 1.83\%$

$\Delta \sin^2 \theta_W = \pm 0.00033$

FFs from backward angle data

arXiv:1802.04759
Parity Violating e$^-$ Scattering (PVES) — Elastic

**Qweak @ CEBAF (JLab)**
- hydrogen (completed)
- $E_e = 1165$ MeV
- $|Q| = 158$ MeV
- $A_{PV} = 2.3 \times 10^{-7}$
- $\Delta A_{PV} = \pm 4.1\%$
- $\Delta Q_W(p) = \pm 6.25\%$
- $\sin^2\theta_W = 0.2383 \pm 0.0011$
- FFs from fit to ep asymmetries
  - arXiv:1905.08283

**P2 @ MESA (JGU Mainz)**
- hydrogen (CDR)
- $E_e = 150$ MeV
- $|Q| = 68$ MeV
- $A_{PV} = 4 \times 10^{-8}$
- $\Delta A_{PV} = \pm 1.4\%$
- $\Delta Q_W(p) = \pm 1.83\%$
- $\Delta \sin^2\theta_W = \pm 0.00033$
- FFs from backward angle data
  - arXiv:1802.04759
Higher-order corrections
Theory issues in PVES

* 1-loop radiative corrections from Marciano & Sirlin
  PRD27 (1983) 552;
  JE & Ramsey-Musolf
  hep-ph/0302149

* WW box enhanced by $\times 7$ relative to Møller scattering

* $\gamma Z$-box uncertainty

* enhanced 2-loop electroweak ($\gamma WW$-double box)

* running weak mixing angle (see later)

* unknown neutron distribution (neutron skin for heavier nuclei)

Blunden et al., arXiv:1102.5334
* largest contribution from DIS region
* largest uncertainty from Regge-VMD model
* non-vanishing at $E_e = 0$ (affects APV)
* total error now at $2 \times 10^{-4}$ (0.3%) level

**Diagram**

Axial box

$Q^2$ ~ $2 \text{ GeV}^2$

$M^2 (M + m_n)^2$ ~ $5 \text{ GeV}^2$

Parton + pQCD

$N\pi$ Res.

Regge + VMD

JE et al., arXiv:1907.07928
\[ \sin^2 \theta_W(0) \text{ and } \Delta \alpha(M_Z) \]

\[
\frac{\mu^2}{d\mu^2} \frac{d\hat{\nu}_f}{d\mu^2} = \frac{\hat{\alpha} Q_f}{24\pi} \left[ \sum_i K_i \gamma_i \hat{\nu}_i Q_i + 12\sigma \left( \sum_q Q_q \right) \left( \sum_q \hat{\nu}_q \right) \right]
\]

\[
\frac{\mu^2}{d\mu^2} \frac{d\hat{\alpha}}{d\mu^2} = \frac{\hat{\alpha}^2}{\pi} \left[ \frac{1}{24} \sum_i K_i \gamma_i Q_i^2 + \sigma \left( \sum_q Q_q \right)^2 \right]
\]

* coupled system of equations  

* \( \Delta \alpha(M_Z) \) had errors in \( \sin^2 \theta_W(0) = \kappa(0) \sin^2 \theta_W(M_Z) \) add because

\[ M_Z^2 \sim g_Z^2(M_Z) v^2 \sim [\alpha / s_W^2 c_W^2](M_Z) G_F^{-1} \]
Dispersive approach: integral over $\sigma(e^+e^- \to \text{hadrons})$ and $\tau$-decay data

- $\alpha^{-1}(M_Z) = 128.947 \pm 0.012$  
  Davier et al., arXiv:1706.09436
- $\alpha^{-1}(M_Z) = 128.958 \pm 0.016$  
  Jegerlehner, arXiv:1711.06089
- $\alpha^{-1}(M_Z) = 128.946 \pm 0.015$  
  Keshavarzi et al., arXiv:1802.02995
- $\alpha^{-1}(M_Z) = 128.949 \pm 0.010$  

- converted from the $\overline{MS}$ scheme and uses $e^+e^-$ annihilation and $\tau$ spectral functions
- PQCD for $\sqrt{s} > 2$ GeV (using $\overline{m}_c$ & $\overline{m}_b$)
- (anti)correlation with $g_\mu - 2$ at two (three) loop order and with $\sin^2\theta_W(0)$
* only experimental input: electronic widths of J/ψ and ψ(2S)
* continuum contribution from self-consistency between sum rules → continuum over-constrained
* include $M_0 \to$ stronger (milder) sensitivity to continuum ($m_c$) Luo & JE, hep-ph/0207114
* quark-hadron duality needed only in finite region (not locally)
* $\bar{m}_c(\bar{m}_c) = 1272 \pm 8 + 2616 \left[ \bar{\alpha}_s(M_Z) - 0.1182 \right]$ MeV
  Masjuan, Spiesberger & JE, arXiv:1610.0853
only experimental input:
  electronic widths of $J/\psi$ and $\psi(2S)$

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This Work
$g_\mu - 2$

**PQCD:** $(a_\mu^{\text{hvp}})^c = (14.6 \pm 0.5_{\text{theory}} \pm 0.2_{mc} \pm 0.1_{\alpha_s}) \times 10^{-10}$

$(a_\mu^{\text{hvp}})^b = 0.3 \times 10^{-10}$

**Lattice gauge theory:**

![Diagram showing lattice results for connected contributions to $a_\mu^{\text{hvp}}$.](chart)

- This work
- Mainz/CLS 19 ($N_f = 3$)
- FNAL-HPQCD-MILC 19
- PACS 19
- ETMC 19
- RBC/UKQCD 18
- BMW 17
- Mainz/CLS 17 ($N_f = 2$)

**Luo & JE, hep-ph/0101010**

**Gérardin et al., arXiv:1904.03120**
### $\sin^2 \theta_W(0)$: flavor separation

<table>
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<tr>
<th>strange quark external current</th>
<th>ambiguous external current</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi$</td>
<td>$\bar{K}K$ (non – $\Phi$)</td>
</tr>
<tr>
<td>$K\bar{K}\pi$ [almost saturated by $\Phi(1680)$]</td>
<td>$K\bar{K}2\pi, K\bar{K}3\pi$</td>
</tr>
<tr>
<td>$\eta\Phi$</td>
<td>$K\bar{K}\eta, K\bar{K}\omega$</td>
</tr>
</tbody>
</table>

* use of result for $\alpha(2$ GeV) also needs isolation of strange contribution $\Delta_s\alpha$

* left column assignment assumes OZI rule

* expect right column to originate mostly from strange current ($m_s > m_{u,d}$)

* quantify expectation using averaged $\Delta_s(g_{\mu}–2)$ from lattices as Bayesian prior


* $\Delta_s\alpha(1.8$ GeV) = $(7.09 \pm 0.32) \times 10^{-4}$ (threshold mass $\bar{m}_s = 342$ MeV $\approx \bar{m}_{s\text{disc}}$)
**sin²θ_W(0): singlet separation**

- use of result for α(2 GeV) needs singlet piece isolation Δ_{disc} α(2 GeV)
- then Δ_{disc} \( \bar{s}^2 = (\bar{s}^2 \pm 1/20) \) Δ_{disc} α(2 GeV) = (− 6 ± 3) × 10⁻⁶
- step function ⇒ singlet threshold mass \( \bar{m}_s^{disc} \approx 350 \) MeV
**sin^2\theta_W(0)**

<table>
<thead>
<tr>
<th>source</th>
<th>uncertainty in sin^2\theta_W(0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta \alpha^{(3)}(2 \text{ GeV}))</td>
<td>1.2\times10^{-5}</td>
</tr>
<tr>
<td>flavor separation</td>
<td>1.0\times10^{-5}</td>
</tr>
<tr>
<td>isospin breaking</td>
<td>0.7\times10^{-5}</td>
</tr>
<tr>
<td>singlet contribution</td>
<td>0.3\times10^{-5}</td>
</tr>
<tr>
<td>PQCD</td>
<td>0.6\times10^{-5}</td>
</tr>
<tr>
<td>Total</td>
<td>1.8\times10^{-5}</td>
</tr>
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</table>

\[ \Rightarrow \sin^2\theta_W(0) = 0.23861 \pm 0.00005_{\text{Z-pole}} \pm 0.00002_{\text{theory}} \pm 0.00001_{\alpha_s} \]

(errors from \(m_c\) and \(m_b\) negligible)
Beyond the Standard Model
Effective couplings (Wilson coefficients)

$[2 \ g^{eu} - g^{ed}]_{AV}$

- P2 (1.7% H asymmetry)
- P2 (0.3% C asymmetry)
- P2 (0.1% He-3/T ratio)
- 2018 (all data)
- 2018 + P2 (H target)
- 2018 + P2 (H + C targets)
- 2018 + P2 (all targets)
- Standard Model prediction
Scale exclusions post Qweak
Beyond the SM

* Z-Z’ mixing: modification of Z vector coupling
* oblique parameters: STU (also need $M_W$ and $\Gamma_Z$)
* new amplitudes: off- versus on-Z pole measurements (e.g. $Z'$)
* dark Z: renormalization group evolution (running)
Related experiments
**Parity Violating e\(^{-}\) Scattering (PVES) — Elastic**

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<th><strong>P2 @ MESA</strong></th>
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<td><strong>H (completed)</strong></td>
<td><strong>H (CDR)</strong></td>
<td><strong>12C (CDR)</strong></td>
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<tr>
<td><strong>E(_e) = 1149 MeV</strong></td>
<td><strong>E(_e) = 155 MeV</strong></td>
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<tr>
<td>**</td>
<td>Q</td>
<td>= 158 MeV**</td>
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<td><strong>APV = 2.3 \times 10^{-7}</strong></td>
<td><strong>APV = 4 \times 10^{-8}</strong></td>
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<td><strong>\Delta Q_{W(p)} = \pm 6.25%</strong></td>
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<td><strong>\Delta sin^2\theta_{W} = \pm 0.0007</strong></td>
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<td><strong>FFs from fit</strong></td>
<td><strong>FFs from backward angles</strong></td>
<td><strong>arXiv:1802.04759</strong></td>
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S and T

- $M_{KK} \gtrsim 3.2 \text{ TeV}$ in warped extra dimension models
- $M_V \gtrsim 4 \text{ TeV}$ in minimal composite Higgs models

Freitas & JE
PDG (2018)
| Experiment  | Data Set  | |Q| (GeV) | A_{PV} | ΔA_{PV} | Δsin^2θ_W | Reference |
|-------------|-----------||--------|--------|--------|--------|---------|
| **E122 @ SLAC** | D (completed) | 0.96 – 1.40 | 1.2 \times 10^{-4} | ± 8% | ± 0.011 | PLB 84, 524 (1979) |
| **PVDIS @ CEBAF** | D (completed) | 1.04 & 1.38 | 1.6 \times 10^{-4} | ± 4.4% | ± 0.0051 | arXiv:1411.3200 |
| **SoLID @ CEBAF** | D (pre-CDR) | 2.1 – 3.1 | 8 \times 10^{-4} | ± 0.6% | ± 0.00057 | Higher twist? Isospin violation? | arXiv:1810.00989 |
Effective couplings (Wilson coefficients)
Parity Violating $e^-$ Scattering (PVES) — Møller

**E158 @ SLC (SLAC)**
- hydrogen (completed)
- $E_e = 45 \& 48 \text{ GeV}$
- $|Q| = 161 \text{ MeV}$
- $A_{PV} = 1.31 \times 10^{-7}$
- $\Delta A_{PV} = \pm 13\%$
- $\Delta Q_W(e) = \pm 13\%$
- $\Delta \sin^2 \theta_W = \pm 0.0013$

**MOLLER @ CEBAF (JLab)**
- hydrogen (proposal)
- $E_e = 11.0 \text{ GeV}$
- $|Q| = 76 \text{ MeV}$
- $A_{PV} = 3.3 \times 10^{-8}$
- $\Delta A_{PV} = \pm 2.4\%$
- $\Delta Q_W(e) = \pm 2.4\%$
- $\Delta \sin^2 \theta_W = \pm 0.00027$
- [arXiv:1411.4088](https://arxiv.org/abs/1411.4088)
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<td><strong>hep-ex/0504049</strong></td>
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PVES history

- Pioneering
- Strange Quark Studies
- Standard Model Tests
- Neutron Radius

Diagram showing the PVES history with various experiments and their results plotted on a log-log scale. The x-axis and y-axis represent the weak mixing angle $\sin^2(2\theta_W)$ and the weak charge $Q_W$, respectively.

- The MESA-P2 experiment at the MESA accelerator employing a 12C target.
- The P2 experiment at the MESA accelerator employing a 12C target.
- The P2 experiment at Bates and in Mainz up to today, parity-violating electron scattering.

The diagram includes a log-log scale and shows the sensitivity of various experiments compared to other determinations. The focus is on parity violation in weak interactions and its measurement in atomic physics and electron scattering.

Further, the diagram highlights the importance of parity violation in establishing the existence of a neutral partner of the charged Pion and its role in the electroweak theory. The weak interaction is the only force that violates parity, and over the past 30 years, the measurement of parity violation has been a well-established observable.

In the Standard Model of Elementary Particle Physics, parity violation in weak interactions has been a well-established observable. Over the past 30 years, the measurement of parity violation has been a well-established observable.

The diagram also shows the energy-scale dependence of the running of the weak mixing angle $\sin^2(2\theta_W)$ over the past 30 years, with predictions for higher energy scales and existing measurements (red points).

The measurement of parity violation in atomic physics and in electron scattering has been a subject of this manuscript. The weak charge of the proton, the electron or the radius of strange quarks to the electromagnetic form factors of the nucleon by measuring its weak electric and magnetic form factors in parity-violating electron scattering. This provides experimental access to the proton's weak charge.

The diagram includes various labels and points representing different experiments and their results, providing a comprehensive overview of the progress in parity-violating electron scattering (PVES) from 1957 to the present day.
Coherent Elastic $\nu$ Nucleus Scattering (CEvNS)

**COHERENT @ SNS**

CsI

$E_\nu \approx 16 - 53$ MeV

$\sigma \sim Q W^2$

$134 \pm 22$ events

constraints on NSI neutron skin?

arXiv:1708.01294

$Q_w(N,Z) = Z (1 - 4 \sin^2 \theta_W) - N$
AG Budker @ JGU Mainz

Ytterbium

$^{170}\text{Yb} - ^{176}\text{Yb}$

± 0.5% per isotope

± 100% error in $\sin^2 \theta_W$

constraints on $Z'$ with $M < 100$ keV

$\Delta \sin^2 \theta_W = \pm 0.2$

neutron skin?

arXiv:1804.05747
Weak mixing angle measurements

\[ A_{FB}^{(e)} \]
\[ A_{FB}^{(\mu)} \]
\[ A_{FB}^{(t)} \]
\[ A_{FB}^{(b)} \]
\[ A_{FB}^{(c)} \]
\[ A_{FB}^{(s)} \]
\[ A_{FB}^{(q)} \]
\[ P^{(\tau)} \]
\[ P_{FB}^{(\tau)} \]
\[ A_{LR}^{(had)} \]
\[ A_{LR}^{(lep)} \]
\[ A_{LR,FB}^{(\mu)} \]
\[ A_{LR,FB}^{(\tau)} \]

CDF (e)
CDF (\mu)
D0 (e)
D0 (\mu)
ATLAS (e)
ATLAS (\mu)
CMS (e)
CMS (\mu)
LHCb (\mu)
\[ Q_{W}^{(e)} \]
\[ Q_{W}^{(p)} \]
\[ Q_{W}^{(Cs)} \]

LEP
SLC
Tevatron
LHC
low energy
world average
SM
Weak mixing angle measurements

2-loop QCD correction with $m_b \neq 0$

Bernreuther et al.  
arXiv:1611.07942

new measured transition vector polarizability

Tho et al.  
arXiv:1905.02768
Weak mixing angle measurements

LEP & SLC:
0.23153 ± 0.00016

Tevatron:
0.23148 ± 0.00033

LHC:
0.23131 ± 0.00033

average direct
0.23149 ± 0.00013

global fit
0.23153 ± 0.00004
Conclusions
Summary and conclusions

* first measurement of proton’s weak charge by Qweak@JLab
* ultra-high precision measurement anticipated at P2@MESA-Mainz
* theory needs refinements
  * ideally full two-loop calculation
  * enhanced three-loop effects
  * $\gamma Z$-box (vector) improvement
  * correction to asymmetry under experiment specific conditions
* but no showstoppers