Precision $\sin^2 \theta_W(Q^2)$ & Electroweak Physics at The EIC (Electron-Ion Collider)

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Based on talks at: W&M, Rockefeller, BNL and U. Washington
Outline

1. General Discussion
2. **WEAK NC PARITY VIOLATION**
   i) APV vs Pol Electron Scattering
   ii) QWEAK, Moller, **DIS (eD&ep)**
3. $\sin^2\theta_W(Q^2)$ Collider Requirements
   For Competitive $A_{RL}$ Program
   $\sim 100 fb^{-1}$ (K. Kumar et al.) 2009 Talk
   Y. Li (Recent)$\rightarrow \Delta \sin^2\theta_W/\sin^2\theta_W=\pm0.2\%$
4. *Utility of Both Beams Polarized*
1. **General Discussion**

Current US On Shore Collider Programs

1) **SLAC** $e^+e^-\rightarrow b\bar{b}$ factory  *(Ended!)*
2) **Fermilab** 2TeV pp Collider
   - Still Higgs Hunting (1-4 More Years?) (8fb$^{-1}\rightarrow16fb^{-1}$)
   - Future $\mu^+\mu^-$ Collider? Needs lots of R&D (20+yrs)
   - Meanwhile high intensity $\nu$ and $\mu$ physics
3) **BNL** RHIC & Polarized pp for Nuclear Physics
   - Luminosity and Detector Upgrades ($\sim$10 yr program)
   - Last Collider Standing! Future polarized ep/elon collider?
     $$L \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$$
4) **JLAB** Fixed Target polarized ep, eN scattering
\[ E_e = 6\text{GeV} \rightarrow 12\text{GeV} \rightarrow ? \quad L \sim 10^{38}\text{cm}^{-2}\text{s}^{-1}! 

**Mainly QCD/Nuclear Physics**
But Flagship A_{LR} ep, ee, eD Experiments
Precision sin^2\theta_W and “New Physics” Effects

**Future** Polarized ep, eD, e^3\text{He}, elon Collider
Goal L \sim 10^{35}\text{cm}^{-2}\text{s}^{-1}!

**US has room for (at most) one EIC**
Cost $500-1000\text{M}$ Affordable if the Physics Case is strong

*(In my view, EIC has a good chance to happen)*

**Partly Because The US Needs a Collider!**
**EIC Physics Case**

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**Must be primarily a Nuclear/QCD Facility**

- Structure functions (pol., PV), small x gluons...
- Properties of quarks in nuclei (EMC effects)...
- Sum rules (Bj) etc, $\alpha(Q^2)_{QCD}$...

HERA($ep$): $L \sim 10^{31} \text{cm}^{-2}\text{s}^{-1} \rightarrow 10^{33,34,35} \text{cm}^{-2}\text{s}^{-1}$

  polarized e,$p$,$D$,$^3He$; Heavy Ions

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**What about Electroweak Physics?**

Second Detector? Complementary Program!
**BNL/LDRD Proposal 2009**

**Electroweak Physics with an Electron-Ion Collider**
(Deshpande, Kumar, Marciano, Vogelsang)

Postdoc: Yingchuan Li

- DIS & Nuclear Structure Functions ($\gamma, Z, W$) (Beyond HERA)
  Bjorken Sum Rule, Polarized EMC, PV Structure Functions…
- $A_{RL}, \sin^2 \theta_W(Q^2)$, Radiative Corrections, *“New Physics”*
- Lepton Flavor Violation: $eg \ e p \rightarrow \tau X$ (1000fb$^{-1}$!)
  Also, $eN \rightarrow \mu X$ vs $\mu N \rightarrow eN$ (Coherent Conversion)

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**Various Issues That Need Thorough Study**

What are the Machine and Detector Requirements?
Inclusion of Electroweak Radiative Corrections (Important?)
Weak Amplitudes Squared vs Photon-Z Interference
High Precision & Polarization ($\pm 0.5\%$, $\pm 0.25\%$?)

**Proton, D, $^3$HE Polarization (Spin Content-Other?)**
2. **WEAK NC PARITY VIOLATION**

**Atomic Parity Violation (APV)**

- $Q_W(Z,N) = Z(1 - 4\sin^2 \theta_W) - N$  
  Weak Charge  
  $\theta_W =$ Weak Mixing Angle

$Q_W(p) = 1 - 4\sin^2 \theta_W = 0.07$

$Q_W^{(209\text{Bi}_{83})} = -43 - 332\sin^2 \theta_W = -127$

Bi Much Larger but Complicated Atomic Physics

Originally APV not seen in Bi $\rightarrow$ SM Ruled Out?  
(Later seen in Tl, Bi, Cs…)

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1978 SLAC Polarized eD Asymmetry (Prescott, Hughes…)

$e + D \rightarrow e + X \gamma$ - Z Interference

$A_{RL} = \sigma_R - \sigma_L / \sigma_R + \sigma_L \propto 2 \times 10^{-4} Q^2 \text{GeV}^{-2} (1 - 2.5\sin^2 \theta_W) \approx 10^{-4}$ Expected

Exp. Gave $A_{RL}^{\text{exp}} = 1.5 \times 10^{-4} \rightarrow \sin^2 \theta_W = 0.21(2)$
Confirmed SU(2)_L x U(1)_Y SM!

±10% Determination of sin^2\theta_W Precision!
Seemed to agree with GUTS (SU(5), SO(10)…)
sin^2\theta^0_W = 3/8 at unification \mu = m_X \sim 2 \times 10^{14}\text{GeV}

\sin^2 \theta_W(m_Z)_{\text{MS}} = 3/8 [1 - 109\alpha / 18\pi \ln(m_X/m_Z) + \ldots]
\approx 0.21! (Great Desert?)

But later, minimal SU(5) ruled out by proton decay exps \tau(p \rightarrow e^+\pi^0) > 10^{33}\text{yr} \rightarrow m_X > 3 \times 10^{15}\text{GeV}

SUSY GUT Unification (m_{\text{susy}} \sim 1\text{TeV}) \rightarrow m_X \sim 10^{16}\text{GeV}
\tau_p \sim 10^{35}-10^{36}\text{yr}

\sin^2 \theta_W(m_Z)_{\text{MS}} = 0.233 (Good Current Agreement!)
1980s - Age of EW Precision

\( \sin^2 \theta_W \) needed better than \( \pm 1\% \) determination

Renormalization Prescription Required

EW Radiative Corrections Computed

Finite and Calculable: DIS \( \nu_\mu N, \nu_\mu e \), APV (A. Sirlin & WJM)

\( m_Z, m_W, \Gamma_Z, A_{LR}, A_{FB} \)

Define Renormalized Weak Mixing Angle: \( \sin^2 \theta_W^R \)

\[ \sin^2 \theta^0_W = 1 - \left( \frac{m_W}{m_Z} \right)^2 = \left( \frac{e^0}{g^0} \right)^2 \] Natural Bare Relation

\[ \sin^2 \theta_W = 1 - \left( \frac{m_W}{m_Z} \right)^2 \] On Shell Definition, Popular in 1980s

Induces large \( \alpha \left( \frac{m_t}{m_W} \right)^2 \) corrections

Now Largely Abandoned

\[ \sin^2 \theta_W(\mu)_{MS} = \frac{e^2(\mu)_{MS}}{g^2(\mu)_{MS}} \] Good for GUT running

No Large RC Induced

Theoretically Nice/ But Unphysical
\[
\sin^2 \theta_W^{lep} = Z_{\mu\mu} \text{ coupling at the Z pole}
\]
very popular at LEP
\[
= \sin^2 \theta_W (m_Z)_{MS} + 0.00028 \text{ (best feature)}
\]

\[
\sin^2 \theta_W (Q^2) = \text{ Physical Running Angle}
\]
Continuous
Incorporates \( \gamma Z \) mixing loops: quarks, leptons, \( W^\pm \)

**Precision measurements at the Z Pole** \( (e^+e^- \rightarrow Z \rightarrow \overline{ff}) \)

**Best Determinations**

\[
\sin^2 \theta_W (m_Z)_{MS} = 0.23070(26) \quad A_{LR} \quad \text{(SLAC)}
\]
\[
\sin^2 \theta_W (m_Z)_{MS} = 0.23193(29) \quad A_{FB}(b\overline{b}) \quad \text{(CERN)}
\]

(3.2 sigma difference!)
• Leptonic vs Hadronic Z Pole Averages

\[ \sin^2 \theta_W(m_Z)_{\text{MS}} = 0.23085(21) \quad \text{Leptonic} \]
\[ \sin^2 \theta_W(m_Z)_{\text{MS}} = 0.23194(27) \quad \text{Hadronic} \]
(Also differ by > 3sigma)

World Average: \( \sin^2 \theta_W(m_Z)_{\text{MS}} = 0.23125(16) \)

IS IT CORRECT?

(Major Implications)
\( \alpha^{-1} = 137.035999 \), \( G_{\mu} = 1.1663788(7) \times 10^{-5} \text{Gev}^{-2} \), \( m_Z = 91.1875 \text{GeV} \)

+ \( m_W = 80.398(25) \text{GeV} \rightarrow \sin^2 \theta_W (m_Z) = 0.23104(15) \)

**Implications:** \( 114 \text{GeV} < m_{\text{Higgs}} < 150 \text{GeV} \).

**New Physics Constraints From:** \( m_W, \sin^2 \theta_W, \alpha, \& G_{\mu} \)

\( S = N_D / 6\pi \) (\( N_D = \# \) of heavy new doublets, eg 4th generation \( \rightarrow N_D = 4 \))

\( m_{W^*} = \) Kaluza-Klein Mass (Extra Dimensions)

\( G_{\mu} \rightarrow G_{\mu} (1 + 0.0085 S + O(1) (m_W / m_{W^*})^2 + \ldots) \)

<table>
<thead>
<tr>
<th>( \sin^2 \theta_W (m_Z)_{\overline{\text{MS}}} )</th>
<th>( S )</th>
<th>( N_D &amp; m_{W^*} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td>0.23125(16)</td>
<td>+0.11(11)</td>
</tr>
<tr>
<td>( A_{LR} )</td>
<td>0.23070(26)</td>
<td>-0.18(15)</td>
</tr>
<tr>
<td>( A_{FB}(b\bar{b}) )</td>
<td>0.23193(29)</td>
<td>+0.46(17)</td>
</tr>
</tbody>
</table>

**Very Different Interpretations. We failed to nail \( \sin^2 \theta_W (m_Z)_{\overline{\text{MS}}} \)!
Loop and Tree Level Corrections to Muon Decay

$\nu_\mu \rightarrow e + W$

$\nu_e \rightarrow \nu_e + Z$

$W \rightarrow b + l$

$H \rightarrow W^* + e$

$W^* \rightarrow W + \nu_e$

$\tilde{Z}' \rightarrow W + W$

$\tilde{W} \rightarrow \tilde{W} + \mu$

$SUSY$

$\nu_e \rightarrow \nu_e + F$

$F \rightarrow W + F'$

$+, ..., Z'$ Boson, SUSY, Technicolor
What about low energy measurements?

- DIS $\nu$ Scattering: $R_\nu \equiv \sigma(\nu_\mu N \rightarrow \nu_\mu X)/\sigma(\nu_\mu N \rightarrow \mu X)$ loops
  $\rightarrow m_t$ heavy, $\sin^2 \theta_W(m_Z)_{\text{MS}} = 0.233 \rightarrow$ SUSY GUTS

  **NuTeV** $\sin^2 \theta_W(m_Z)_{\text{MS}} = 0.236(2)$ High?

  Rad. Corr.? Nuclear-Charge Symmetry Violation?

**Meanwhile: Atomic Parity Violation:**

1990 $Q_W(Cs)^{\text{exp}} = -71.04(1.38)(0.88)$ C. Wieman et al.

Electroweak RC $\rightarrow Q_W(Cs)^{\text{SM}} = \rho_{PV}(-23 - 220 \kappa_{PV}(0) \sin^2 \theta_W(m_Z)_{\text{MS}})$

$= -73.19(3)$

1999 $Q_W(Cs)^{\text{exp}} = -72.06(28)(34)$ Better Atomic Th.

2008 $Q_W(Cs)^{\text{exp}} = -72.69(28)(39) \rightarrow \sin^2 \theta_W(m_Z)_{\text{MS}} = 0.2290(22)$

2009 $Q_W(Cs)^{\text{exp}} = -73.16(28)(20) \rightarrow \sin^2 \theta_W(m_Z)_{\text{MS}} = 0.2312(16)!$

$\pm 0.5\% \rightarrow$ Major Constraint On “New Physics”

$Q_W(Cs) = Q_W(Cs)^{\text{SM}}(1 + 0.011S - 0.9(m_Z/m_{Z\chi})^2 + \ldots)$

eg $S = 0.0 \pm 0.4$ $m_{Z\chi} > 1.2$TeV, leptoquarks, …
Radiative Corrections to APV

\[ Q_W(Z,N) = \rho_{PV} (-N + Z (1 - 4\kappa_{PV} \sin^2 \theta_W (m_Z)_{MS})) \]

\[ \rho_{PV} = 1 - \alpha / 2\pi (1/s^2 + 4(1-4s^2)(\ln(m_Z/M)^2 + 3/2) + ...) \approx 0.99 \]

\[ \kappa_{PV}(0) = 1 - \alpha / 2\pi s^2 \left( \left( \frac{9 - 8s^2}{8s^2} \right) + \left( \frac{9}{4} - 4s^2 \right) (1 - 4s^2) \left( \ln(m_Z/M)^2 + \frac{3}{2} \right) \right) - \frac{2}{3} \sum (T_{3f} Q_f - 2s^2 Q_f^2) \ln(m_Z/m_f)^2 + ... \approx 1.003 \]

\[ s^2 = \sin^2 \theta_W (m_Z)_{MS} = 0.23125, \quad M = \text{Hadronic Mass Scale} \]

Radiative Corrections to APV small and insensitive to hadronic unc.

Same Corrections Apply to elastic eN scattering as \( Q^2 \to 0, \quad E_e \ll m_N \)
E158 at SLAC Pol ee→ee Moller
$E_e \approx 50\text{GeV}$ on fixed target, $Q^2 = 0.02\text{GeV}^2$

$A_{LR}(ee) = -131(14)(10) \times 10^{-9} \alpha (1-4\sin^2\theta_W)$

**EW Radiative Corrections ** $\sim -50\%$! (Czarnecki & WJ)

Measured to $\pm 12\% \rightarrow \sin^2\theta_W$ to $\pm 0.6\%$

$\rightarrow \sin^2\theta_W(m_Z)_{\text{MS}} = 0.2329(13)$ slightly high

**Best Low $Q^2$ Determination of $\sin^2\theta_W$**

$A_{LR}(ee)^{\text{exp}} = A_{LR}(ee)^{\text{SM}}(1+0.13T-0.20S+7(m_Z/m_{Z\chi})^2\ldots)$

**Constrains** “New Physics” eq $m_{Z\chi} > 0.6\text{TeV}$, $H^-, S$, Anapole Moment, …

Together APV(Cs) & E158 $\rightarrow \sin^2\theta_W(Q^2)$ running

$\sin^2\theta_W(m_Z)_{\text{MS}} = 0.232(1)$ about $\pm 0.5\%$
Running $\sin^2 \theta$
Goals of Future Experiments

• High Precision: $\Delta \sin^2 \theta_W \sim 0.0004$ or better
• Low $Q^2$ Sensitivity to “New Physics”
  $m_Z > 1 \text{ TeV}$, $|S| < 0.1-0.2$, SUSY Loops, Extra Dim.,
  4th Generation….
Other $A_{LR}$ Experiments

**Strange Quark Content Program**: Bates, JLAB, MAMI

Proton strange charge radius and magnetic moment consistent with 0. Axial Vector effects and RC cloud strangeness.

**PREX Experiment**: Neutron distribution

Preparing the way for future experiments, pushing technology and instrumentation, polarization
Future Efforts

QWEAK exp at JLAB

Will measure forward $A_{LR}(ep \rightarrow ep) \propto (1-4\sin^2\theta_W)=Q_W(p)$

$E=1.1\text{GeV}, Q^2 \approx 0.03\text{GeV}^2, \text{Pol}=0.80 \pm 1\% \rightarrow A_{RL}(ep) \approx 3 \times 10^{-7}$

small $A_{RL}$ requires long running

Goal $\Delta \sin^2\theta_W(m_Z)_{MS} = 0.0008$ via $\pm 4\%$ measurement of $A_{LR}$

Will be best low energy measurement of $\sin^2\theta_W$

$A_{LR}(ep)^{exp} = A_{LR}(ep)^{SM}(1+4(m_Z/m_{Z\chi})^2+\ldots)$

eg $m_{Z\chi} \sim 0.9\text{TeV}$ Sensitivity (Not as good as APV)

• The Gorchtein - Horowitz Nightmare (PRL)
  
  $\gamma Z$ box diagrams: $O(2\alpha E_e/\pi m_p) \approx 6\%$ of $Q_W(p)$!

Recently Confirmed (Improved): Sibirtev et al.; Gorchtein et al.

Proposed Qweak Theory Uncertainty $< 2\%$

JLAB Flagship Experiment
Other Future Efforts: Polarized Moller at JLAB
After 12GeV Upgrade
\[ A_{LR}(ee \rightarrow ee) \text{ to } \pm 2.5\% \]
\[ \Delta \sin^2 \theta_W (m_Z)_{MS} = \pm 0.00025! \]
Comparable to Z pole studies!
\[ A_{LR}(ee)^{\text{exp}} = A_{LR}(ee)^{\text{SM}}(1 + 7(m_Z/m_{Z\chi})^2 + \ldots) \]
Explores \( m_{Z\chi} \rightarrow 1.5\text{TeV} \) Better than APV, \( S \sim 0.1 \) etc.

Future JLAB Flagship Experiment!

Very Hard To Do Better!

ep Collider Goal: \( \pm 0.2\% \)
\[ H_{PV} = G_{\mu}/\sqrt{2} \left[ (C_{1u} \bar{u} \gamma^\nu u + C_{1d} \bar{d} \gamma^\nu d) e_\gamma \gamma_5 e + (C_{2u} \bar{u} \gamma \gamma_5 u + C_{2d} \bar{d} \gamma \gamma_5 d) e_\gamma e + \ldots \right] \]

\[ Q_W(p) = 2(2C_{1u} + C_{1d}) \]
\[ Q_W(Cs) = 2(188C_{1u} + 211C_{1d}) \]

Not renormalized by strong interactions at \( Q=0 \)

What about the \( C_{2q} \)?
What About $C_{2u}$ and $C_{2d}$?

- Renormalized at low $Q^2$ by Strong Interactions

Measure in Deep-Inelastic Scattering (DIS), eD & ep

$$A_{RL}(eD \rightarrow eX) \propto 2 \times 10^{-4} \text{GeV}^{-2} Q^2 \left[ (C_{1u} - C_{1d}/2) + f(y)(C_{2u} - C_{2d}/2) \right]$$

$$f(y) = \frac{1 - (1-y)^2}{1 + (1-y)^2}$$

**Standard Model:**

- $C_{1u} = \frac{(1 - 8 \sin^2 \theta_W/3)}{2} \approx 0.20$
- $C_{1d} = -\frac{(1 - 4 \sin^2 \theta_W/3)}{2} \approx -0.32$
- $C_{2u} = \frac{(1 - 4 \sin^2 \theta_W)}{2} \approx 0.04$
- $C_{2d} = -\frac{(1 - 4 \sin^2 \theta_W)}{2} \approx -0.04$

$C_{2q}$ sensitive to RC & “New Physics” eg $Z\chi$ (SO(10))

Measure $A_{RL}$ to $\pm 1/2\%$?

Measure $C_{2q}$ to $\pm 1-2\%$? Theory (loops)?
JLAB 6 GeV DIS eD→eX  Proceeding
JLAB 12 GeV DIS eD  Future
Goals: Measure $C_{2q}$s, “New Physics”, Charge Sym. Violation …

Effective Luminosity (Fixed Target) $10^{38}$ cm$^{-2}$sec$^{-1}$!

What can ep and eD at e-ion contribute?
Asymmetry F.O,M,$\sim A^2 N$, $A \propto Q^2$, $N \propto 1/Q^2$ (acceptance?)
High $Q^2$ Better (but Collider Luminosity?)
K. Kumar Talk $\rightarrow$100fb$^{-1}$ ($L\sim 10^{34}$cm$^{-2}$s$^{-1}$) Needed

Program can be started with lower luminosity
Do DIS ep, eD, eN at factor of 10 lower
(Polarized p & Nuclei)$\rightarrow$Bjorken Sum Rule, Pol Structure Functions, Spin Distribution…
Single and Double Polarization Asymmetries

Polarized e: \( A^{e}_{RL} = \frac{(\sigma_{RR} + \sigma_{RL} - \sigma_{LL} - \sigma_{LR})}{(\sigma_{RR} + \sigma_{RL} + \sigma_{LL} + \sigma_{LR})} \propto P_e \)

Polarized p: \( A^{p}_{RL} = \frac{(\sigma_{RR} + \sigma_{LR} - \sigma_{RL} - \sigma_{LL})}{(\sigma_{RR} + \sigma_{LR} + \sigma_{RL} + \sigma_{LL})} \propto P_p \)

Polarized e&p \( A^{ep}_{RRLL} = \frac{(\sigma_{RR} - \sigma_{LL})}{(\sigma_{RR} + \sigma_{LL})} \propto P_{eff} \)

\[ P_{eff} = \frac{(P_e - P_p)}{(1 - P_e P_p)} \] opposite signs
like relativistic velocities addition \( \leq 1 \)

eg \( P_e = 0.8 \pm 0.008, \ P_p = -0.7 \pm 0.03 \rightarrow P_{eff} = 0.962 \pm 0.004 \)
small uncertainty

How to best utilize \( P_{eff} \)?

Measure: \( \sigma_{RR}, \sigma_{LL}, \sigma_{RL}, \sigma_{LR} \) Fit \( \rightarrow \) Polarization Dist.
Example: Polarized Protons or Deuterons
(Unpolarized Electrons)

\[ C_{1q} \leftrightarrow C_{2q} \propto (1-4\sin^2\theta_w) \]

Use to measure \( \sin^2\theta_w \)?
LDRD $A_{RL}$ GOALS

Examine Machine and Detector Requirements For $\pm 1\% \ A_{RL}$
Include EW Radiative Corrections to DIS
Is 100 fb$^{-1}$ Sufficient?  $(Y. \ Li \rightarrow X \sin^2 \theta_W / \sin^2 \theta_W = \pm 0.2\%)$
Utility of Proton Polarization?
Stage 1 e-ion aim for $\pm 4\%$
Determine EW Structure Functions
Study Nuclear Effects (EMC, CSV, Sum Rules)
Important Secondary e-ion Goal? Improves Proposal?