Parity Violating Electron Scattering

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PHY 599
PVES Outline

Introduction
• What is it?
• What can it do?

MOLLER Experiment
• How is it measured?

Conclusion
• Why does it matter?
• Summary
• Looking Forward
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• 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by $\theta_w$.
• 1973 – Weak neutral current ($Z^0$ mediated interaction) in neutrino scattering is discovered at CERN’s Gargamelle bubble chamber.
• 1978 – Parity Violation was first observed in neutral current by the SLAC E122 experiment measuring polarized electron scattering off of deuterium.
  ➢ E122 found $\sin^2 \theta_w = 0.22(2)$, matching theoretical predictions, establishing the Standard Model (SM) of particle physics.
• 1980s – It was determined that $\sin^2 \theta_w$ was needed to high precision to verify predictions of theoretical calculations.
  ➢ Radiative corrections cause $\sin^2 \theta_w$ to change as a function of energy scale (typically taken to be $Q^2$, the momentum transfer of a reaction).
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What can PVES do?

- The two main $\sin^2\theta_W$ results from High Energy Physics (from Large Electron Positron Collider and SLAC Large Detector) disagree with each other by up to $3\sigma$.
- Therefore further measurements are desired.

![Graphs showing $\sin^2\theta_W$ vs. $\mu$ and $Q$](image)

Data from 5 best measurements

Theoretical contributions from bosons and fermions, along with world data.
What can PVES do?

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- Since PVES is sensitive to the accuracy of radiative corrections in theoretical SM calculations it can be used as a precision tool to verify the SM.
What can PVES do?

• The two main $\sin^2 \theta_w$ results from High Energy Physics (from Large Electron Positron Collider and SLAC Large Detector) disagree with each other by up to $3\sigma$.
• Therefore further measurements are desired.
• Since PVES is sensitive to the accuracy of radiative corrections in theoretical SM calculations it can be used as a precision tool to verify the SM.
• It can also be used to provide lower bounds on the energy scale of new physics Beyond the Standard Model (BSM).

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{(1 + \delta)\Lambda^2} \sum_{i,j=L,R} \eta_{ij}^f \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j,$$

$$\Lambda \approx \frac{2\sqrt{\pi}}{\sqrt{\sqrt{2}G_F \Delta Q^e_W}}$$
What can PVES do?

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MOLLER

- One such PVES experiment proposes to measure $A_{pV}$ to within 0.7 ppb within the decade.
- This will get a $\pm 0.1\%$ measurement of $\sin^2 \theta_w$.
- Yielding ideally a lower bound on new physics up to the $\Lambda = 19$ TeV range, rivaling collider based searches.
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Measurement of a Lepton Lepton Electroweak Reaction

Uses Møller scattering to measure parity violating $e^- \rightarrow e^-$ scattering asymmetry.

Tree level contributions from photon and Z bosons

1-loop radiative corrections
MOLLER

Measurement of a Lepton Lepton Electroweak Reaction

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- The primary contribution to the PV part of the cross section in Møller scattering comes from interference between the photon and Z boson exchange diagrams.

- To overcome the photon cross section dominance we look at the difference (asymmetry) between the helicity flipped cross-sections, sensitive to parity violation in the neutral current interference.
MOLLER

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$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE \frac{G_F}{\sqrt{2\pi\alpha}} \frac{4\sin^2 \theta}{(3 + \cos^2 \theta)^2} Q^e_W$$

$$= mE \frac{G_F}{\sqrt{2\pi\alpha}} \frac{2y(1-y)}{1 + y^4 + (1-y)^4} Q^e_W$$

$G_F$ = Fermi coupling constant, $Q^e_W = 1 - 4\sin^2 \theta_W$, $\alpha = 1/137$, $E =$ incident beam energy, $m =$ electron mass, $\theta =$ center of mass scattering angle, $y \equiv 1 - \frac{E'}{E}$, where $E'$ = energy of one of the scattered electrons.
MOLLER

Plans to measure of $\sin^2\theta_w$ at unprecedented precision in $Q^2 << M_Z^2$ region
JLab - CEBAF
Thomas Jefferson National Accelerator Facility
Continuous Electron Beam Accelerator Facility

5 ½ passes through pairs of ~1 GeV Linacs

12 GeV Upgrade JLab aerial view
MOLLER

• This experiment builds on many preceding experiments.
  ➢ MIT Bates C12
  ➢ SAMPLE
  ➢ HAPPEX
  ➢ SLAC E158
  ➢ PREX
  ➢ QWEAK
This experiment builds on many preceding experiments:
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$A_{PV}$ is orders of magnitude smaller than the precision of any single measurement of the asymmetry.

Typically dominated by instrumental noise and background asymmetries.
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Solution

• Collect large quantities of data to maximize statistics.
• Simultaneously measure backgrounds.
• Suppress noise in accelerator and detectors.
MOLLER CAD rendering
MOLLER
How to overcome high precision hurdles?
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• High quality beam
  - 11 GeV lab frame electrons.
  - ~ 90%, highly polarized.
  - ~ 85 micro-amp electron beam.
  - Rapid helicity switching, etc.
  - Beam monitoring feedback.
  - Online polarimetry.

• 1.92kHz Helicity switching, ~500 micro s pulses.
• Multiple efforts, switch helicity over long time scales.
• Pseudorandom opposite helicity windows.
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• Liquid hydrogen target
  - 150 cm long, 5cm radius target cell.
  - Cryogenically cooled.

SLAC E158 liquid hydrogen target design
MOLLER

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• Novel hybrid toroid spectrometer
  ➢ Separate Møllers & background.
  ➢ Full azimuthal acceptance.

Bends low energy, high angle electrons less
And higher energy, low angle electrons more
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Hybrid toroid magnet section view showing 7 segments.
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Kinematics of blocking half of the symmetrical Møller events with odd number of coils.
MOLLER CAD rendering
How to overcome high precision hurdles?

- High quality beam
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- Precision beam monitoring
  - Online polarimetry

- Liquid hydrogen target
  - 150 cm long, 5cm radius target cell
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- Novel hybrid toroid spectrometer
  - Gas Electron Multipliers (GEMs) used for kinematic calibrations.
  - Møllers all focused to one band of integrating quartz detectors.
  - Separate Møllers & background.
  - Full azimuthal acceptance.
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• Signal and background as a function of radius.
• Showing the planned segmentation to catch the different signals as independently as possible.
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- Asymmetry background and normalized asymmetry background as a function of radius at the detector plane, as well as normalized asymmetry.
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- Novel hybrid toroid spectrometer
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  - Full azimuthal acceptance.
- Integrating detectors
  - Can also run counting calibrations.
  - Average out raw asymmetries.
  - Reduces dead-time between counts.

- Two viable designs for PMTs at the end of light guides connecting them to Čerenkov radiating quartz blocks.
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\( \sin^2 \theta_w \) is still not known very precisely:

- There is room for many approaches to illuminate new physics.

As stated before, MOLLER has the potential to

- Test Standard Model predictions at the highest precision.
- Probe BSM physics to TeV scale, comparable to HEP.
- Pave the way for future experiments in the precision frontier that serve to compliment and inform the ongoing searches at the edge of the energy frontier.

You never know where new physics will come from
Summary

• The strength of the weak force is theoretically well known.
• There are many ways to go about measuring its strength.
• MOLLER is an example of an experiment that will push the low $Q^2$ precision limits.
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Looking Forward

• There are many experiments on the horizon that aim to make similar measurements, ranging from Atomic Parity Violation (APV) to further precision measurements of $\sin^2\theta_w$ at other $Q^2$.
• It is possible to make a series of measurements at the proposed Electron Ion Collider (EIC).
References

- MOLLER Conceptual Design Review (Sept. 1, 2015)
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\[
\begin{pmatrix}
\gamma \\
Z^0
\end{pmatrix}
= 
\begin{pmatrix}
\cos \theta_W & \sin \theta_W \\
-\sin \theta_W & \cos \theta_W
\end{pmatrix}
\begin{pmatrix}
B^0 \\
W^0
\end{pmatrix}
\]

Where \( \tan \theta_W = \frac{g'}{g} \), for the theory’s coupling constants \( g \) and \( g' \), or in terms of the electromagnetic coupling, 

\[ e = \frac{gg'}{\sqrt{g^2 + g'^2}} \], such that \( \sin \theta_W = \frac{e}{g} \), \( \cos \theta_W = \frac{e}{g'} \).
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$$m_W = m_{Z^0} \cos \theta_W$$
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  Radiative corrections cause $\sin^2 \theta_w$ to change as a function of energy scale (typically taken to be $Q^2$, the momentum transfer of a reaction).

\[
\sin^2 \theta_W(Q^2) = \kappa(Q^2) \sin^2 \theta_W(m_Z)
\]

where $\kappa(Q^2)$ carries the 1-loop radiative corrections with it. $\kappa(Q^2 = m_Z^2) \equiv 1$, and $\kappa(Q^2 = 0) \simeq 1.03$, which is a nearly 3% shift. Experiments that measure the weak charge of the electron

\[
Q_w^e = 1 - 4 \sin^2 \theta_W
\]

see a 40% shift, from 0.075 to 0.46 (at $Q \simeq 0.1 GeV$)
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