Parity Violating Electron Scattering

Cameron Clarke

Nov 16, 2015

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

PVES Outline

Introduction

- What is it?
- What can it do?

MOLLER Experiment

- How is it measured?

Conclusion

- Why does it matter?
- Summary
- Looking Forward

What is PVES?

- 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
- 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by θ_w.
- 1971 – T'Hooft proves renormalizability for gauge theories with spontaneous symmetry breaking.
- 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).

PVES Outline

Introduction

- What is it?
- What can it do?

MOLLER Experiment

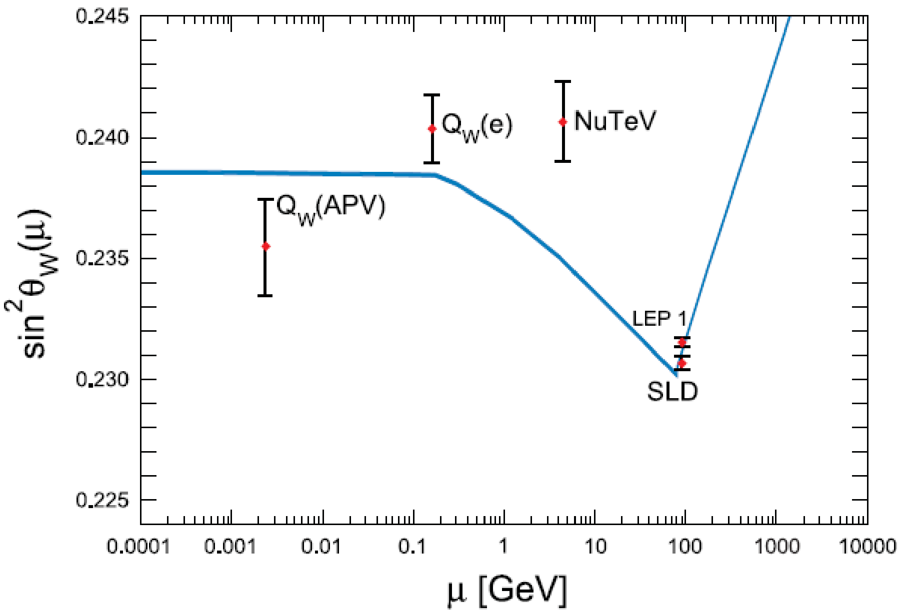
- How is it measured?

Conclusion

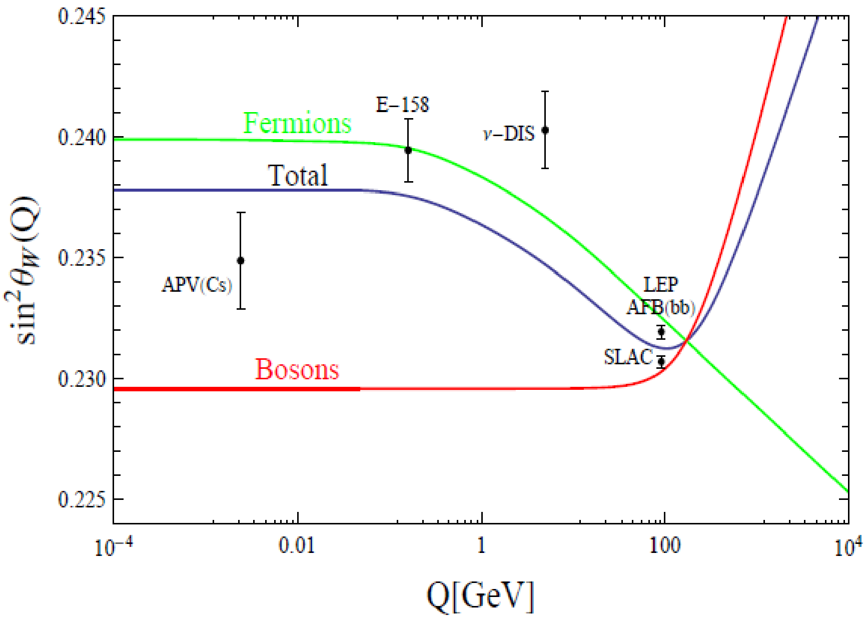
- Why does it matter?
- Summary
- Looking Forward

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 3σ.
- Therefore further measurements are desired.



Data from 5 best measurements



Theoretical contributions from bosons and fermions, along with world data.

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 3σ.
- 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.

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 3σ.
- 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).

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

$$\Lambda \simeq \frac{2\sqrt{\pi}}{\sqrt{\sqrt{2} G_F \Delta Q^e_W}}$$

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 3σ.
- 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).

MOLLER

- One such PVES experiment proposes to measure A_{PV} to within 0.7 ppb within the decade.
- This will get a ±0.1% measurement of $Sin^2\theta_w$.
- Yielding ideally a lower bound on new physics up to the Λ = 19 TeV range, rivaling collider based searches.

PVES Outline

Introduction

- What is it?
- What can it do?

MOLLER Experiment

- How is it measured?

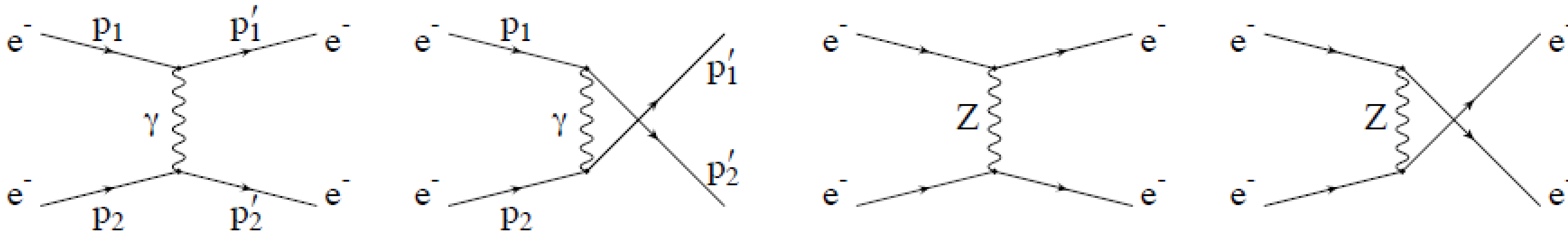
Conclusion

- Why does it matter?
- Summary
- Looking Forward

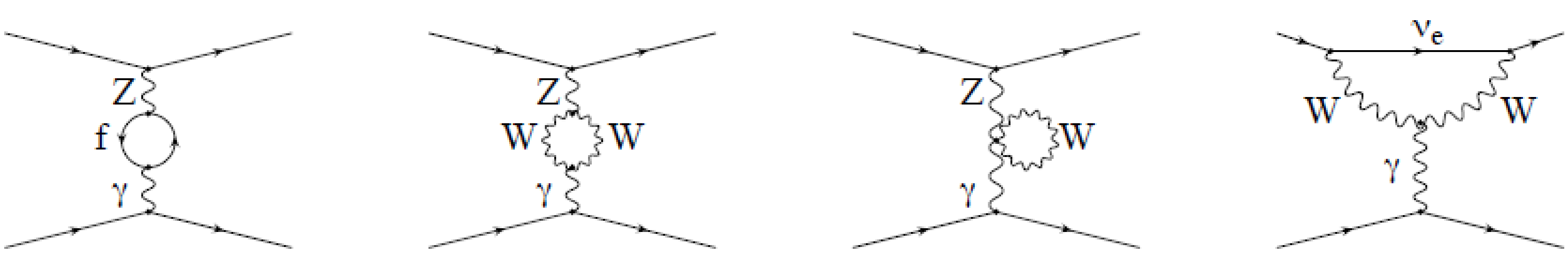
MOLLER

Measurement of a Lepton Lepton Electroweak Reaction

Uses Møller scattering to measure parity violating e^- -> e^- scattering asymmetry.



Tree level contributions from photon and Z bosons



1-loop radiative corrections

MOLLER

Measurement of a Lepton Lepton Electroweak Reaction

Uses Møller scattering to measure parity violating e^- -> e^- scattering asymmetry.

- 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

Measurement of a Lepton Lepton Electroweak Reaction

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

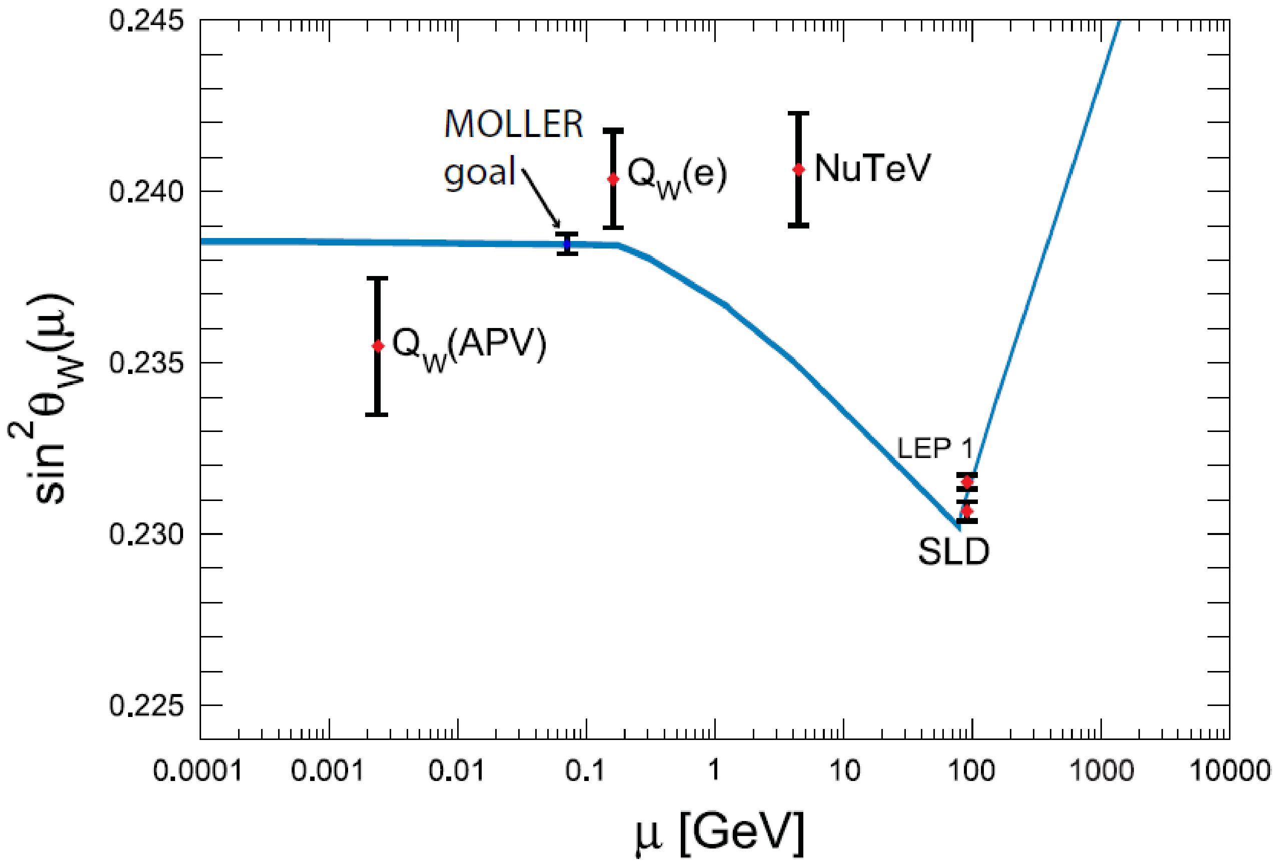
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q_W^e$$

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

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

MOLLER

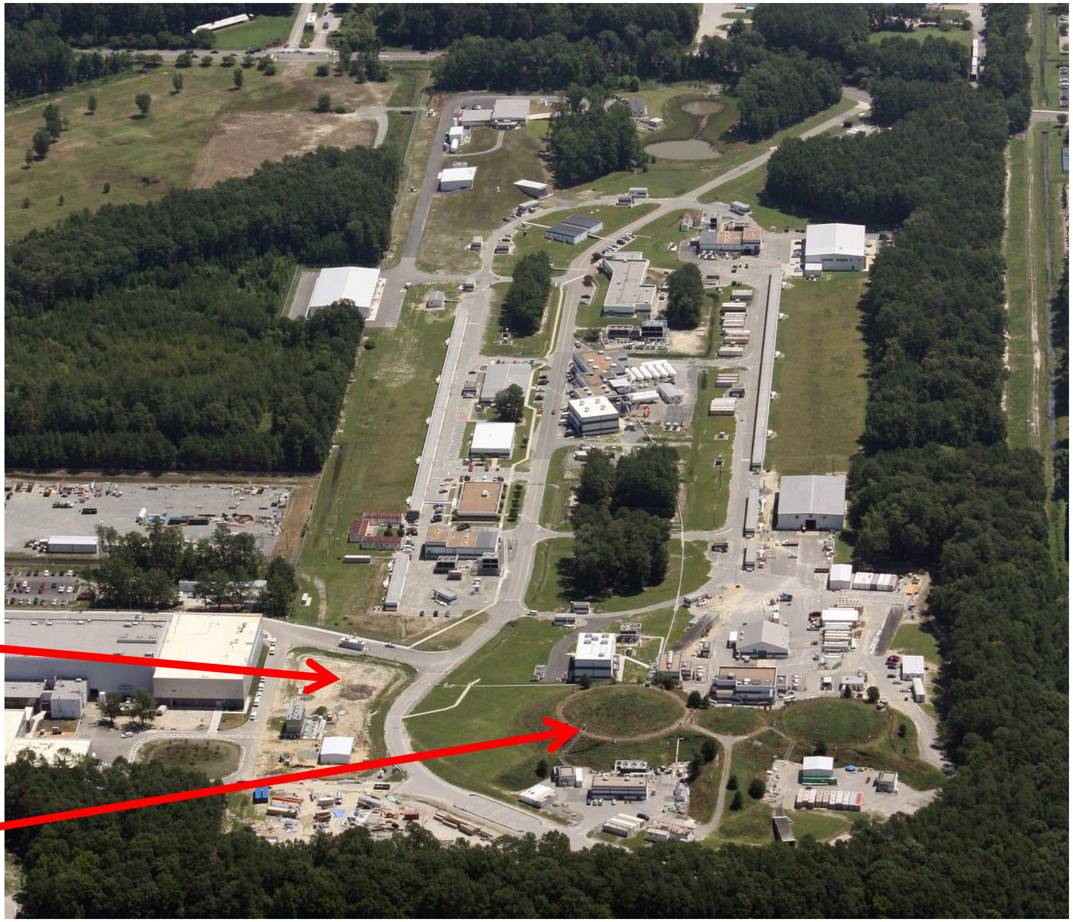
Plans to measure of $Sin^2\theta_w$ at unprecedented precision in $Q^2 << M_Z^2$ region



JLab - CEBAF

Thomas Jefferson National Accelerator Facility
Continuous Electron Beam Accelerator Facility

5 ½ passes through pairs of ~1 GeV Linacs



Injector

Hall A

12 Gev Upgrade JLab aerial view

MOLLER

- This experiment builds on many preceding experiments.
  - MIT Bates C12
  - SAMPLE
  - HAPPEX
  - SLAC E158
  - PREX
  - QWEAK

MOLLER

- This experiment builds on many preceding experiments.
  - MIT Bates C12
  - SAMPLE
  - HAPPEX
  - SLAC E158
  - PREX
  - QWEAK
- 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.

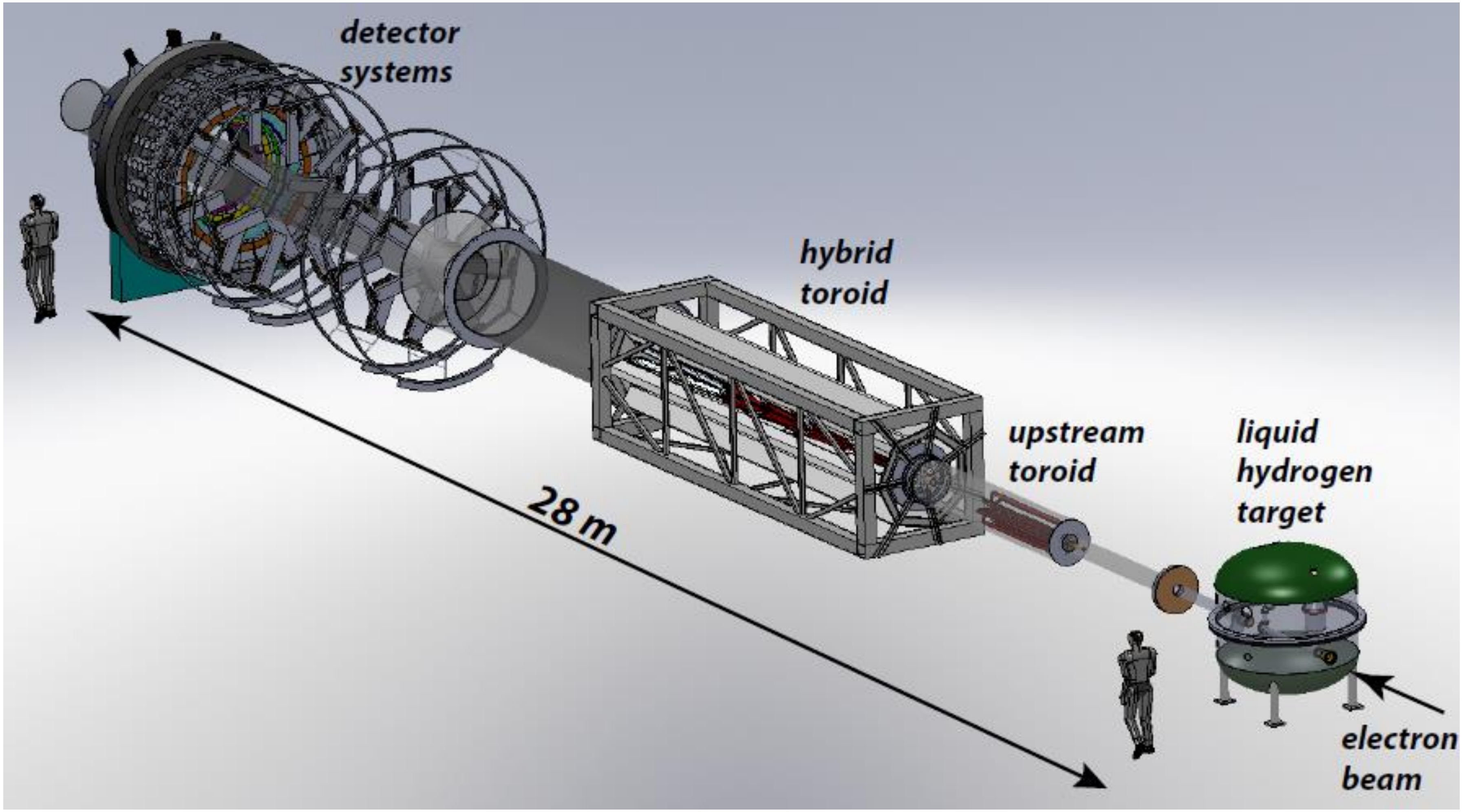
MOLLER

- This experiment builds on many preceding experiments.
  - MIT Bates C12
  - SAMPLE
  - HAPPEX
  - SLAC E158
  - PREX
  - QWEAK
- 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.

Solution

- Collect large quantities of data to maximize statistics.
- Simultaneously measure backgrounds.
- Suppress noise in accelerator and detectors.

MOLLER



MOLLER CAD rendering

MOLLER

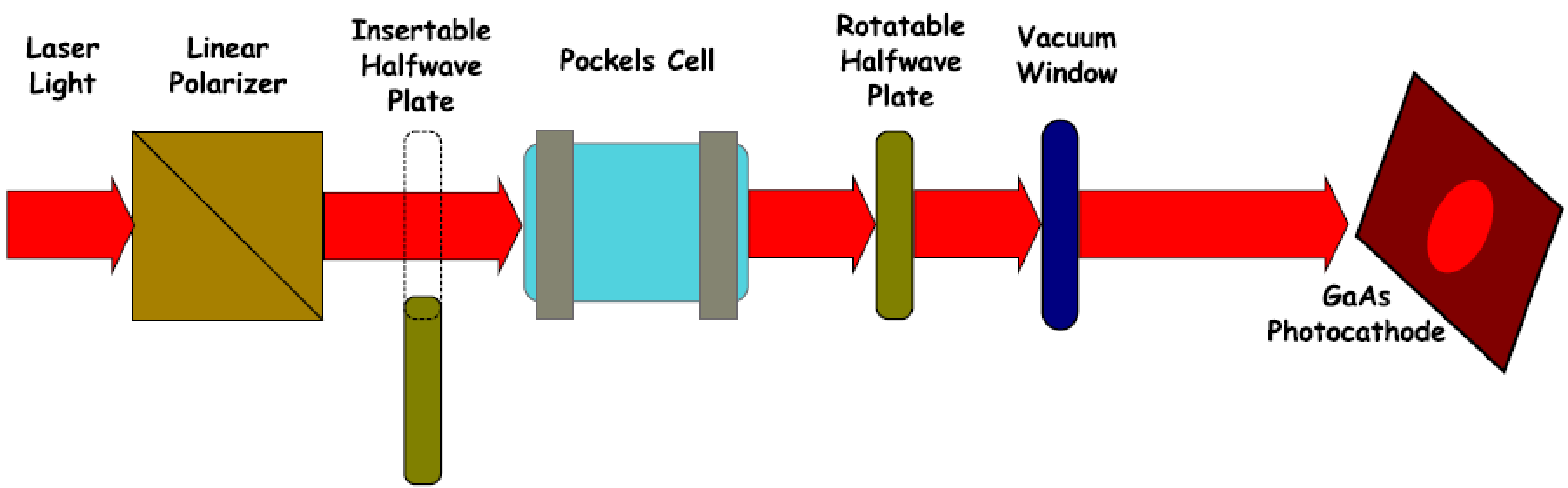
How to overcome high precision hurdles?

MOLLER

How to overcome high precision hurdles?

- 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.

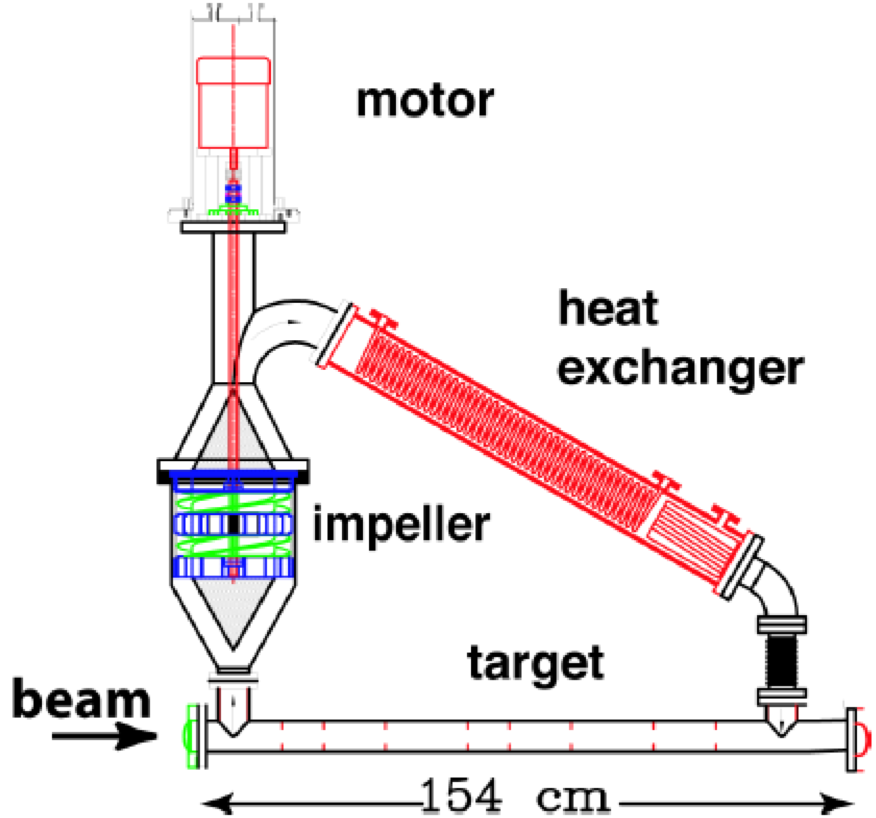
- 1.92kHz Helicity switching, ~500micro s pulses.
- Multiple efforts, switch helicity over long time scales.
- Pseudorandom opposite helicity windows.



MOLLER

How to overcome high precision hurdles?

- 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.
- Liquid hydrogen target
  - 150 cm long, 5cm radius target cell.
  - Cryogenically cooled.

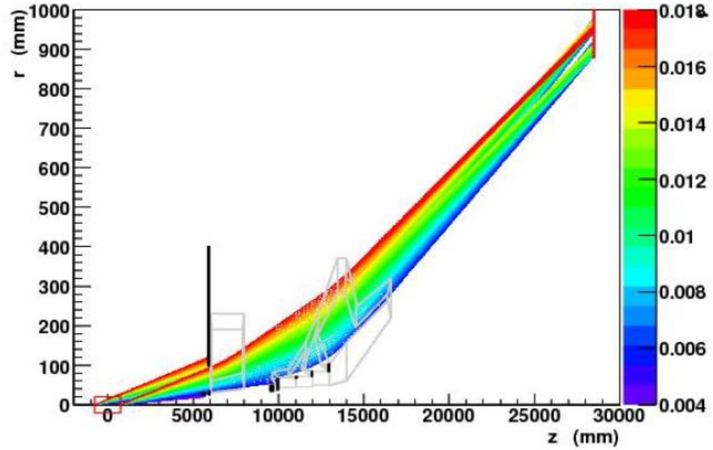


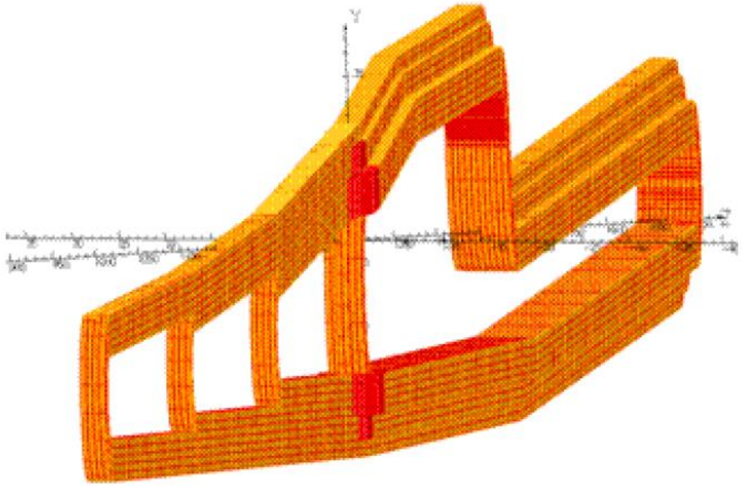
SLAC E158 liquid hydrogen target design

MOLLER

How to overcome high precision hurdles?

- 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.
- Liquid hydrogen target
  - 150 cm long, 5cm radius target cell.
  - Cryogenically cooled.
- Novel hybrid toroid spectrometer
  - Separate Møllers & background.
  - Full azimuthal acceptance.



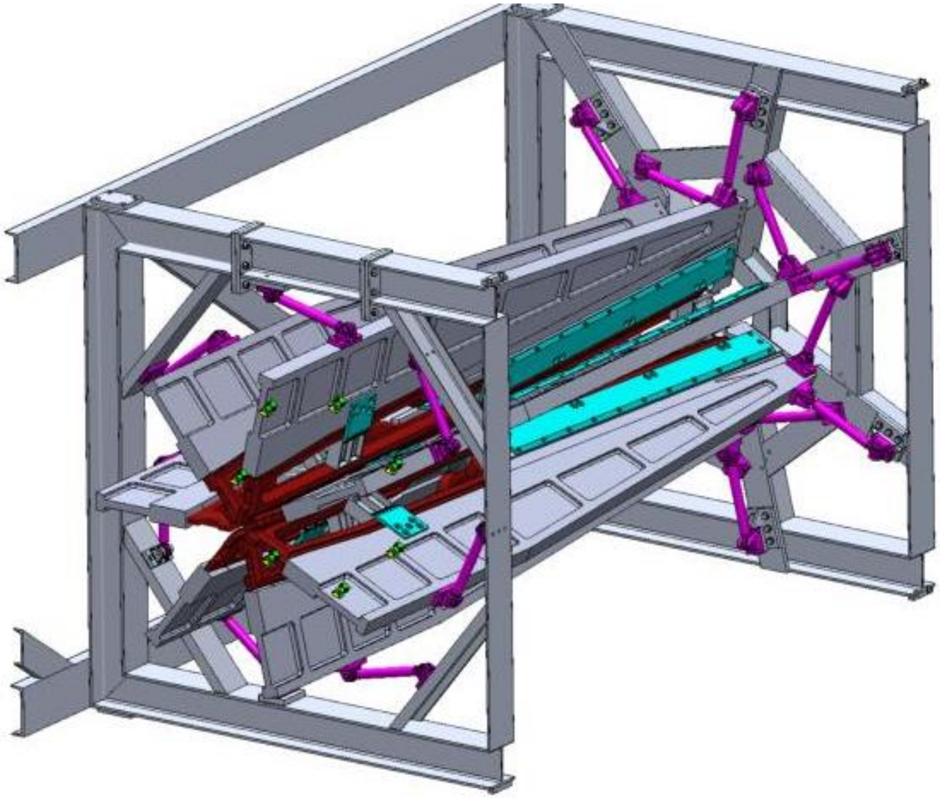


Bends low energy, high angle electrons less
And higher energy, low angle electrons more

MOLLER

How to overcome high precision hurdles?

- 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.
- Liquid hydrogen target
  - 150 cm long, 5cm radius target cell.
  - Cryogenically cooled.
- Novel hybrid toroid spectrometer
  - Separate Møllers & background.
  - Full azimuthal acceptance.

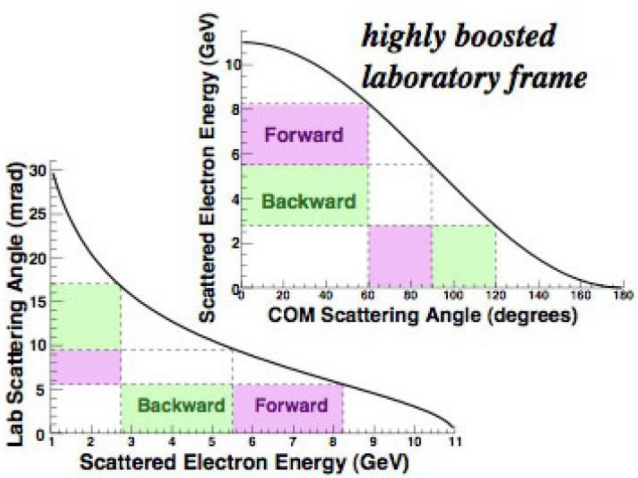


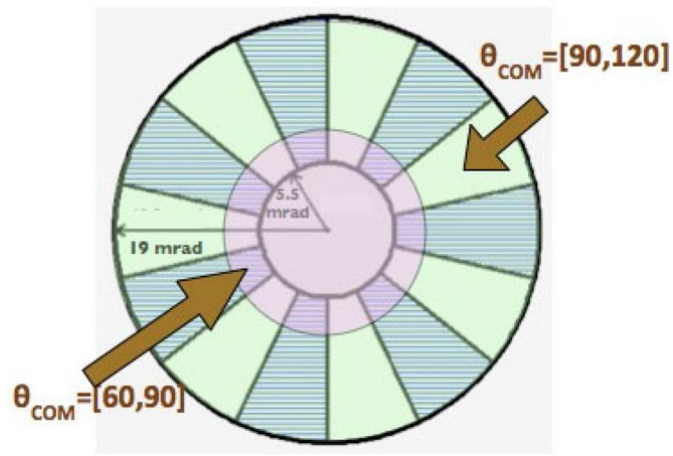
Hybrid toroid magnet section view showing 7 segments.

MOLLER

How to overcome high precision hurdles?

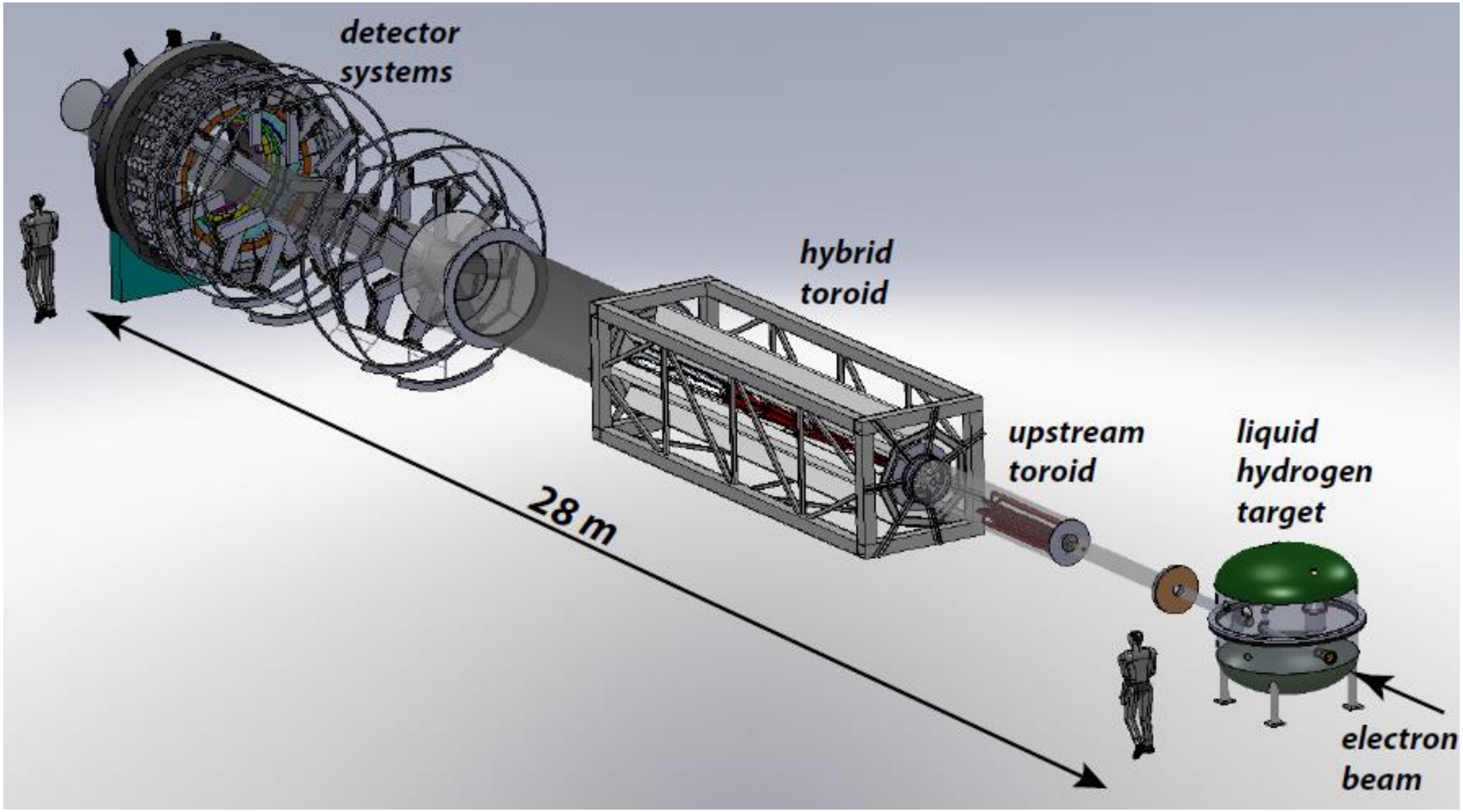
- High quality beam
  - 11 GeV lab frame electrons.
  - ~ 90%, highly polarized.
  - ~ 85 micro-amp electron beam.
  - Rapid helicity switching, etc.
  - Beam monitoring feedback.
  - Online polarimetry.
- Liquid hydrogen target
  - 150 cm long, 5cm radius target cell.
  - Cryogenically cooled.
- Novel hybrid toroid spectrometer
  - Separate Møllers & background.
  - Full azimuthal acceptance.





Kinematics of blocking half of the symmetrical Møller events with odd number of coils.

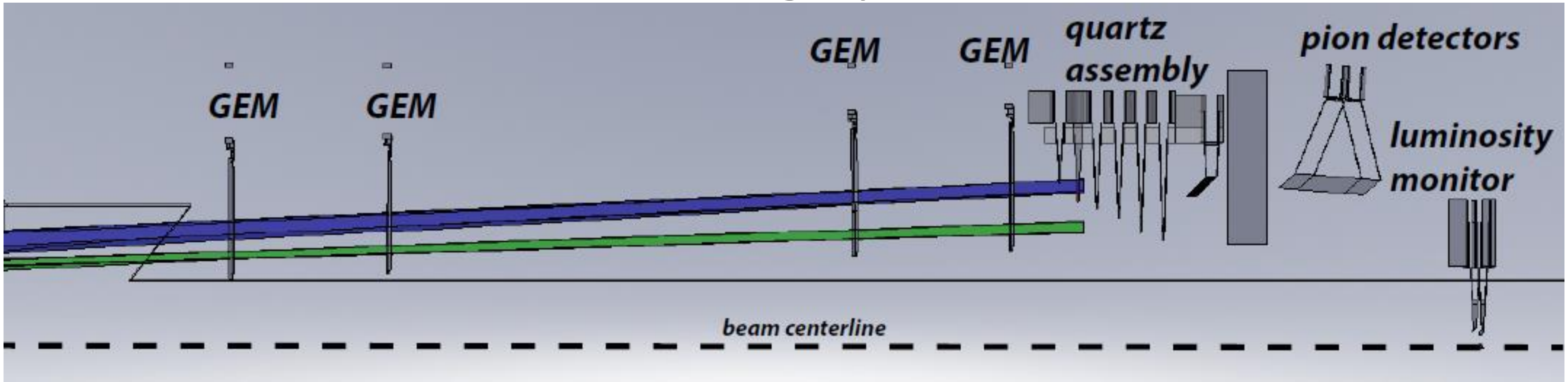
MOLLER



MOLLER CAD rendering

MOLLER

How to overcome high precision hurdles?



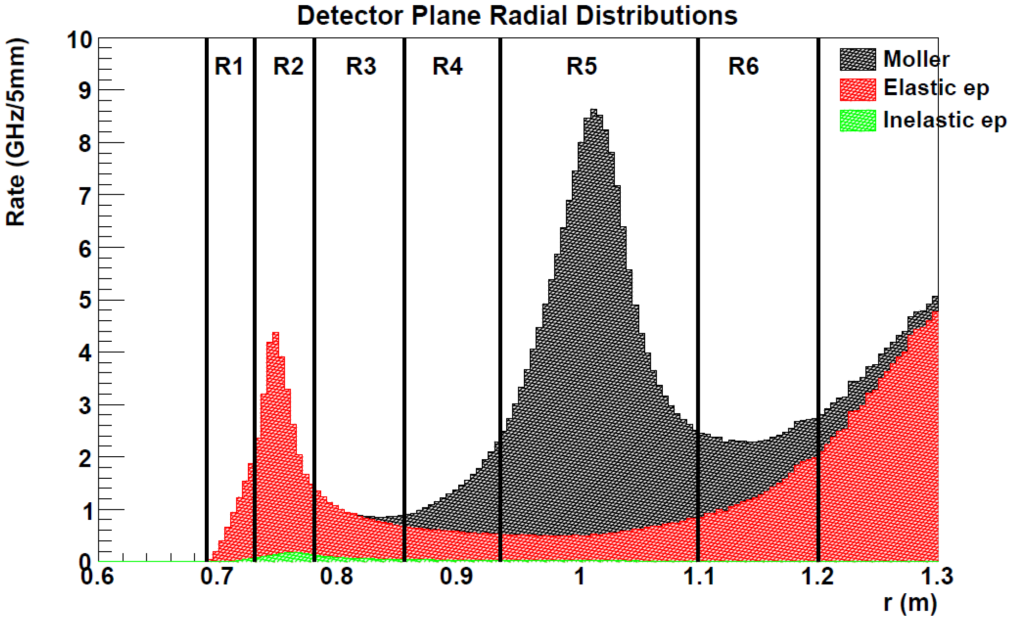
- **Gas Electron Multipliers (GEMs) used for kinematic calibrations.**
- **Møllers all focused to one band of integrating quartz detectors.**

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

MOLLER

How to overcome high precision hurdles?

- 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.
- Liquid hydrogen target
  - 150 cm long, 5cm radius target cell.
  - Cryogenically cooled.
- Novel hybrid toroid spectrometer
  - Separate Møllers & background.
  - Full azimuthal acceptance.

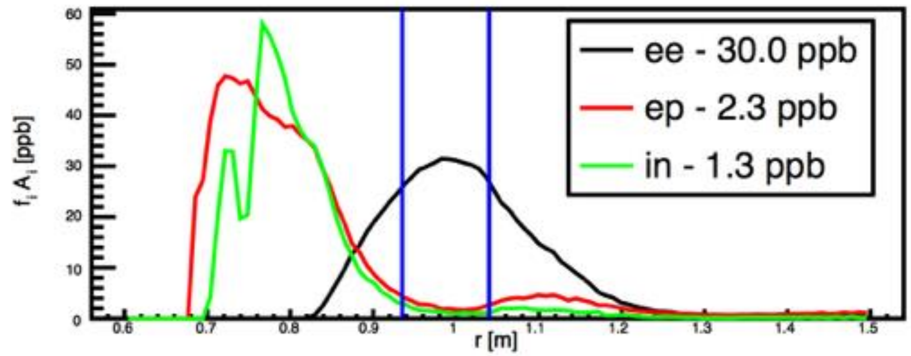


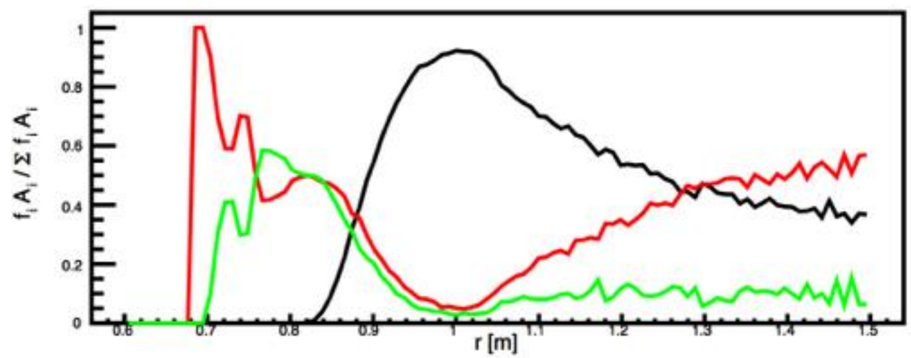
- **Signal and background as a function of radius.**
- **Showing the planned segmentation to catch the different signals as independently as possible.**

MOLLER

How to overcome high precision hurdles?

- 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.
- Liquid hydrogen target
  - ➢ 150 cm long, 5cm radius target cell.
  - ➢ Cryogenically cooled.
- Novel hybrid toroid spectrometer
  - ➢ Separate Møllers & background.
  - ➢ Full azimuthal acceptance.



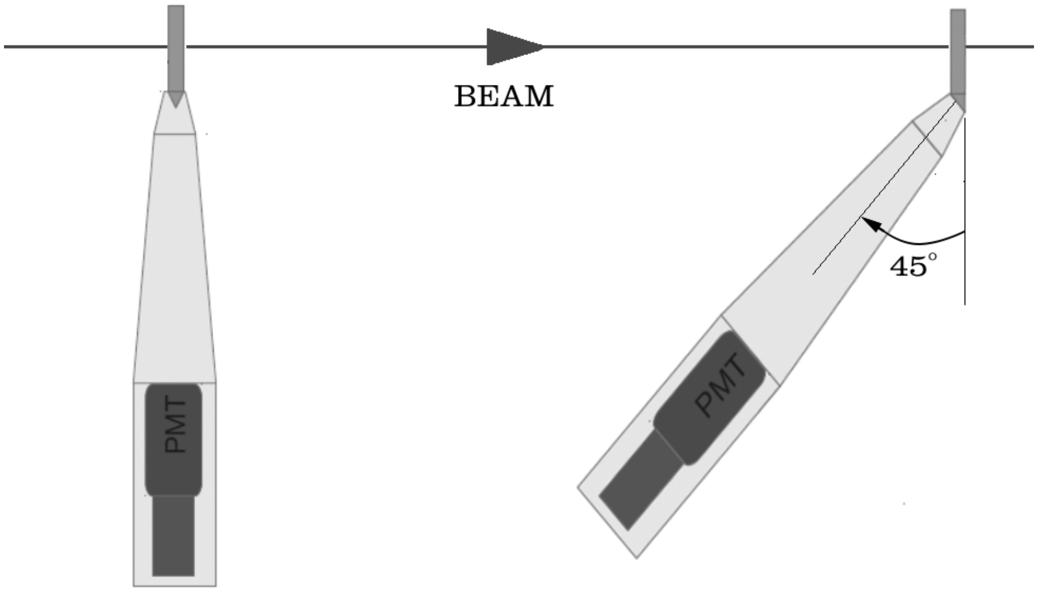


- **Asymmetry background and normalized asymmetry background as a function of radius at the detector plane, as well as normalized asymmetry.**

MOLLER

How to overcome high precision hurdles?

- 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.
- Liquid hydrogen target
  - 150 cm long, 5cm radius target cell.
  - Cryogenically cooled.
- Novel hybrid toroid spectrometer
  - Separate Møllers & background.
  - 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.**

MOLLER

How to overcome high precision hurdles?

- 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.
- Liquid hydrogen target
  - 150 cm long, 5cm radius target cell.
  - Cryogenically cooled.
- Novel hybrid toroid spectrometer
  - Separate Møllers & background.
  - Full azimuthal acceptance.
- Integrating detectors
  - Can also run counting calibrations.
  - Average out raw asymmetries.
  - Reduces dead-time between counts.

PVES Outline

Introduction

- What is it?
- What can it do?

MOLLER Experiment

- How is it measured?

Conclusion

- Why does it matter?
- Summary
- Looking Forward

$Sin^2\theta_w$ 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

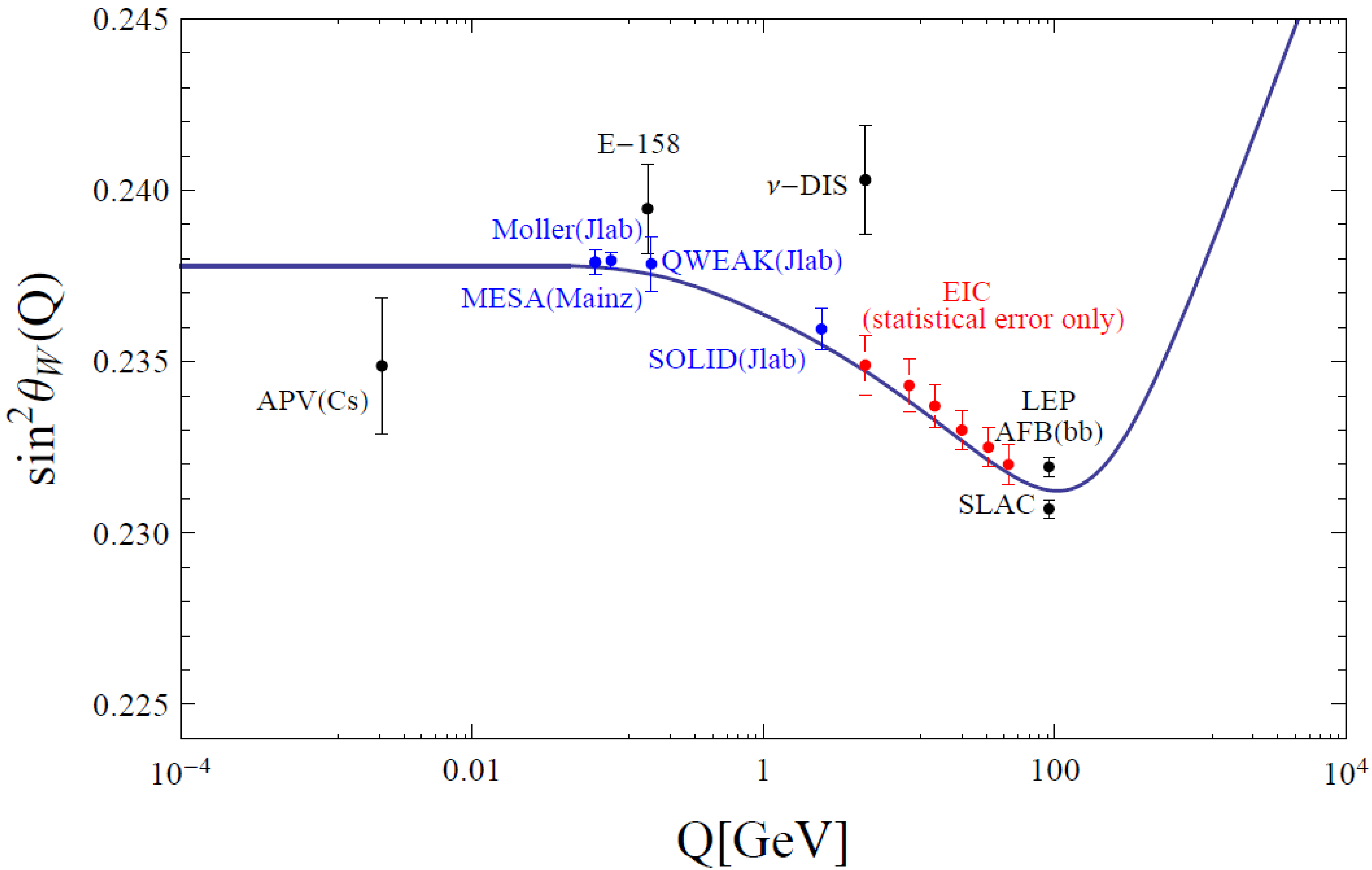
- The strength of the weak force is theoretically well known.
- There are many ways to go about measuring its strength.
- MOLLER is an example of an experiment that will push the low Q^2 precision limits.

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.

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).


0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(Q)$
E−158
ν−DIS
Moller(Jlab)
QWEAK(Jlab)
MESA(Mainz)
EIC
(statistical error only)
SOLID(Jlab)
APV(Cs)
LEP
AFB(bb)
SLAC
10^{-4}
0.01
1
100
10^4
Q[GeV]

References

- MOLLER Proposal, arXiv:1411.4088v2 (2014)
- MOLLER Conceptual Design Review (Sept. 1 , 2015)
- “Low-Energy Measurements of the Weak Mixing Angle.” K.S.Kumar, et. al., Ann. Rev. Nucl. Part. Sci. 63 (2013) 237-267

What is PVES?

- 1961 – Weak mixing angle formalism developed by Sheldon Glashow.

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

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 $\sin\theta_W = \frac{e}{g}$, $\cos\theta_W = \frac{e}{g'}$

What is PVES?

- 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
- 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by θ_w.

$$m_W = m_{Z^0} \cos\theta_W$$

What is PVES?

- 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
- 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by θ_w.
- 1971 – T'Hooft proves renormalizability for gauge theories with spontaneous symmetry breaking.

What is PVES?

- 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
- 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by θ_w.
- 1971 – T'Hooft proves renormalizability for gauge theories with spontaneous symmetry breaking.
- 1973 – Weak neutral current (Z^0 mediated interaction) in neutrino scattering is discovered at CERN's Gargamelle bubble chamber.

What is PVES?

- 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
- 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by θ_w.
- 1971 – T'Hooft proves renormalizability for gauge theories with spontaneous symmetry breaking.
- 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.

$$A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

- ➢ E122 found $\mathrm{Sin}^2\theta_w = 0.22(2)$, matching theoretical predictions, establishing the Standard Model (SM) of particle physics.

What is PVES?

- 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).

$$\sin^2\theta_W(Q^2) = \kappa(Q^2)\sin^2\theta_W(m_Z)$$

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 $Q \simeq 0.1GeV$)

What is PVES?

- 1961 – Weak mixing angle formalism developed by Sheldon Glashow.
- 1967 – Weinberg adds Higgs mechanism and relates gauge boson masses by θ_w.
- 1971 – T'Hooft proves renormalizability for gauge theories with spontaneous symmetry breaking.
- 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).