Parity Violation in MOLLER Scattering

A Search for New Physics at the TeV Scale

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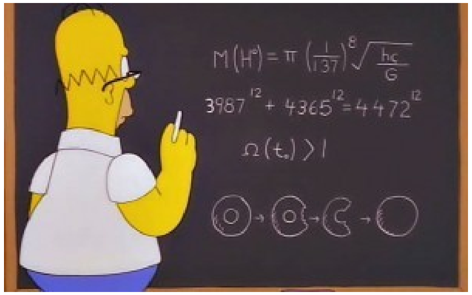
Outline

- The Standard Model (SM)
- Parity Violating Electron Scattering (PVES) overview
- Parity Violation (PV) in Møller Scattering
- MOLLER Experiment
- Summary

Standard Model of Particle Physics

- Quarks : Strong interaction (QCD)
- Leptons : Electroweak interactions (EW)
- Bosons : force mediation
- They are all elegantly contained in,
  - $SU(3)_C \times SU(2)_L \times U(1)_Y$
- SM is very successful!
  - Latest : Higgs boson
- But...
  - Why observable universe is mostly matter not anti-matter?
  - Why neutrinos oscillations (mixed states)?
  - Why three families of quarks and leptons?
  - What about gravity and dark matter?



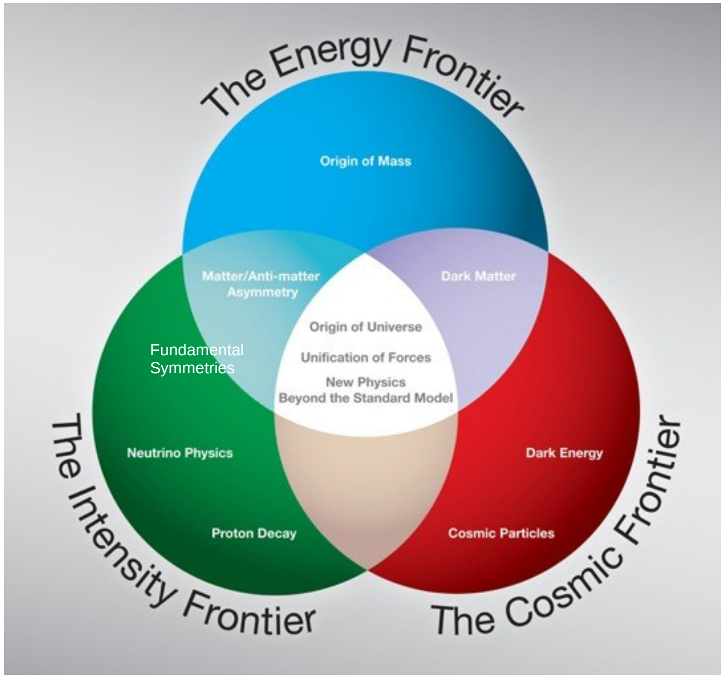
Some have claimed that Homer Simpson predicted the Higgs boson a 1998 episode of “The Simpsons” called “The Wizard of Evergreen Terrace,”!

Testing SM and Physics Beyond SM

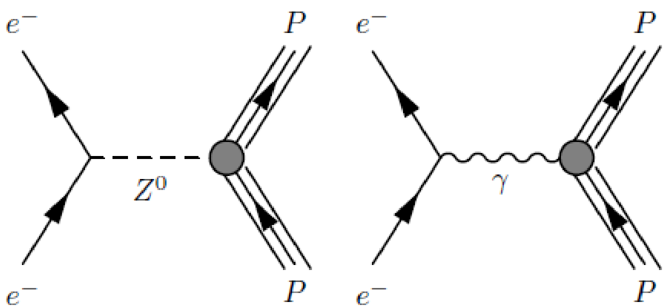
Standard Model is a "Low energy" effective theory

And there are three approaches to uncover underlying physics

- Energy frontier: direct searches for new particles ← High energy
  - Tevatron and LHC
- Cosmic frontier : Cosmic rays, cosmic wave background, and dark matter ← Broad range of energies
  - Fermi telescope : dark matter signatures
  - Planck satellite : CMB
- Precision or intensity frontier: searches for indirect effects ← Low/modest energy
  - EDM searches, rare decays, double beta decays
  - Parity violation in electron scattering



Parity Violating Electron Scattering



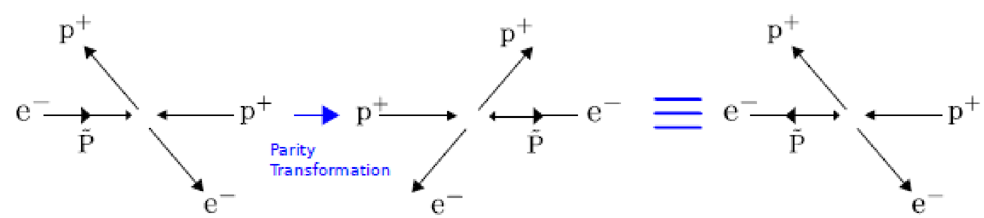
$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q_\ell l^\mu J_\mu^{EM}$$

$$M^{NC} = \frac{-G_F}{2\sqrt{2}} (g_V^\ell l^\mu + g_A^\ell l^{\mu 5})(J_\mu^{NC} + J_{\mu 5}^{NC})$$

Differential scattering cross section,

$$\frac{d\sigma}{d\Omega} \propto |M^{Total}|^2 \simeq |M^{EM}|^2$$

Due to PV nature of the neutral current, the differential cross section is dependent on the helicity of the electron



The difference in helicity correlated scattering cross section is known as the PV asymmetry,

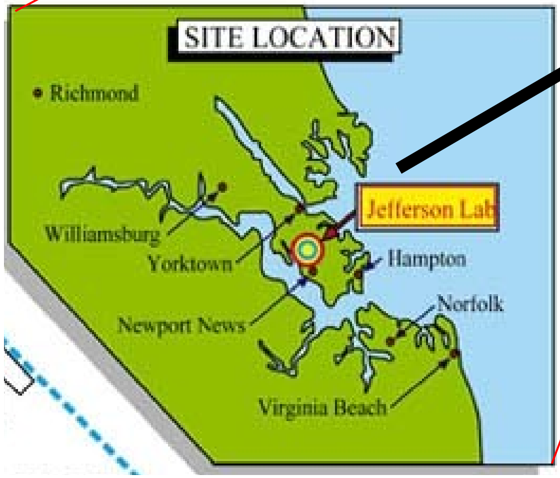
$$A_{PV} = \frac{\frac{d\sigma^R}{d\Omega} - \frac{d\sigma^L}{d\Omega}}{\frac{d\sigma^R}{d\Omega} + \frac{d\sigma^L}{d\Omega}} \propto \frac{M^{EM} \cdot M^{NC}}{|M^{EM}|^2}$$

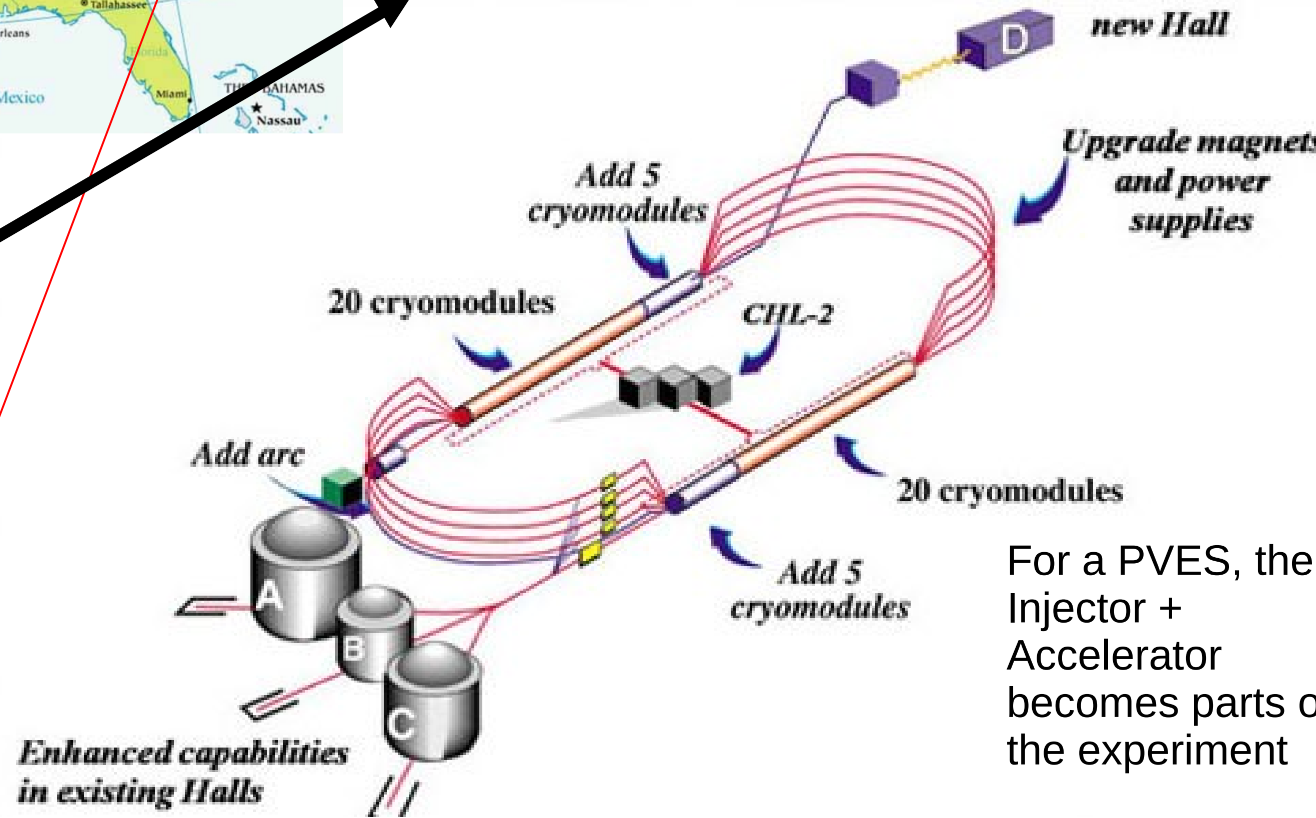
Parity Violating Electron Scattering

Challenges in PVES

- Very small PVES asymmetries
  - In the order of 10^{-6} to 10^{-9}
  - Need so many electron scattering events
- High intensity
  - High electron beam current and longer targets for more luminosity
- High electron beam polarization
- High precision
  - Custom detectors (low noise) and dedicated electronics (high precision)
  - Measure electron beam polarization high precision (~ 1%)
  - Keep many different systematic effects under control

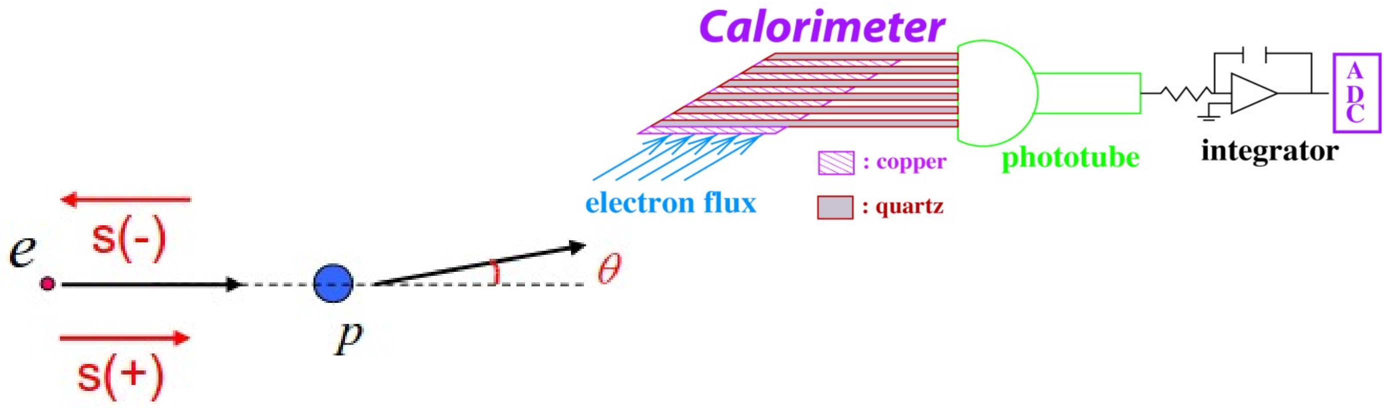
Continuous Electron Beam Accelerator Facility @ Jefferson Lab

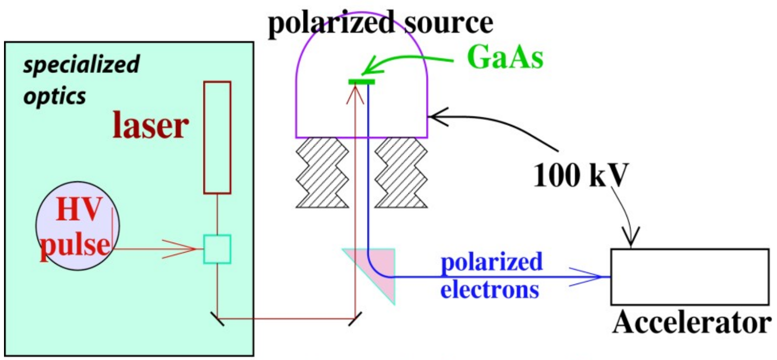




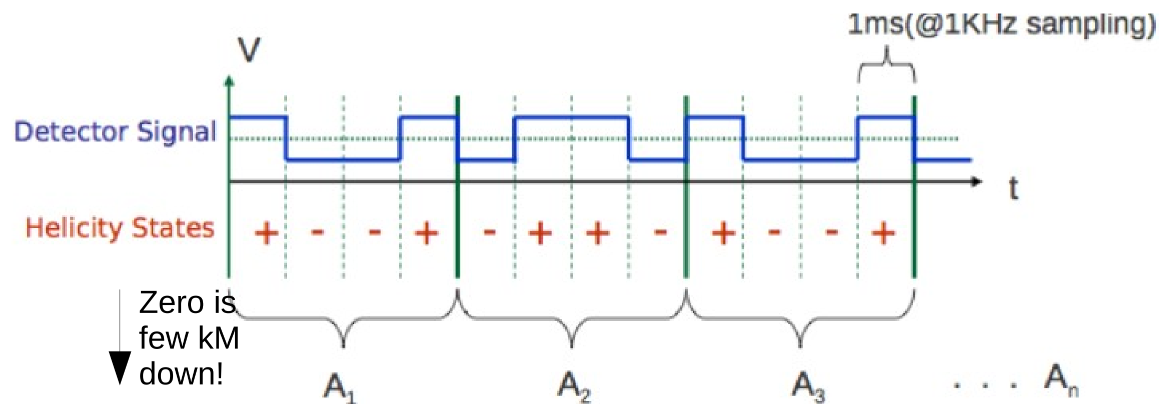
For a PVES, the Injector + Accelerator becomes parts of the experiment

How to Do A PVES Experiment





rapid, random, helicity flipping



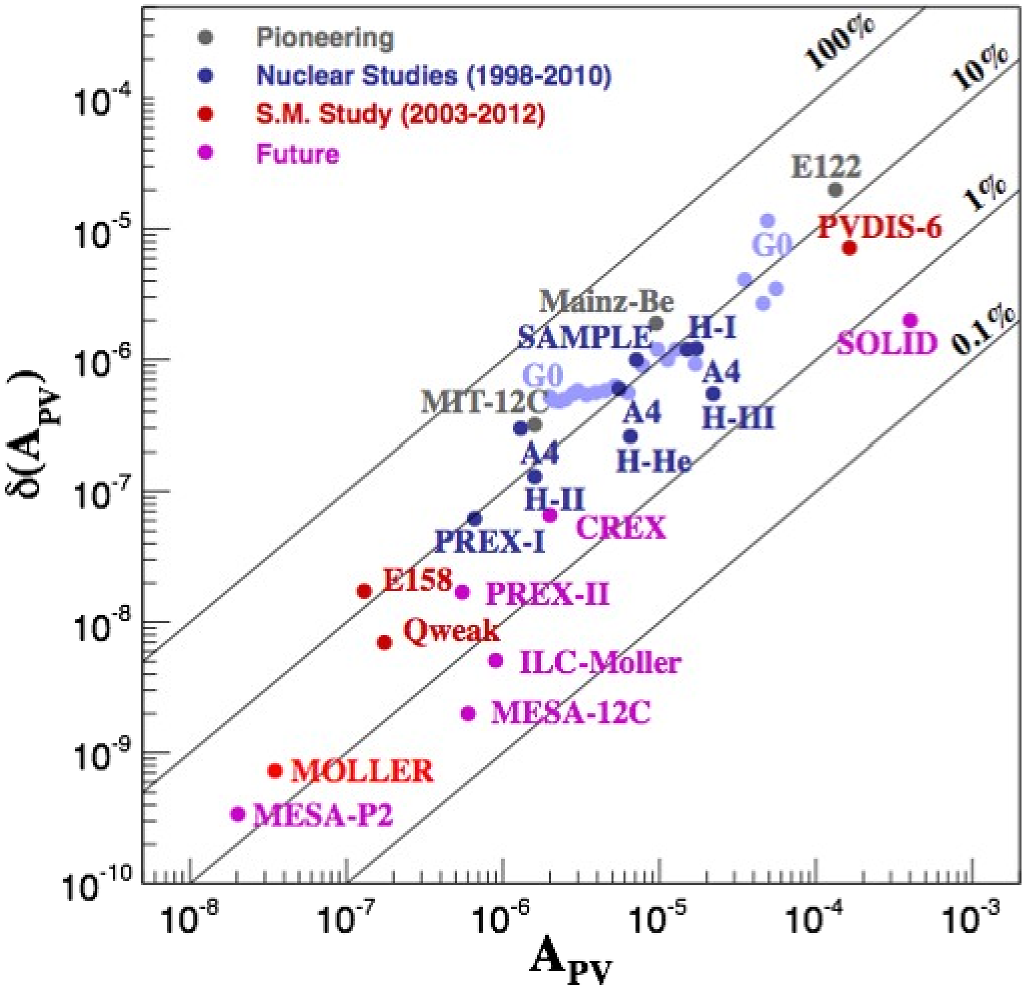
Helicity of electron beam flipped periodically, delayed helicity reporting to prevent direct electrical pick up of reversal signal by detectors

Detector signal integrated for each helicity window and asymmetry formed by quartet (QRT)

PVES Progress

Looking to Future : Technical challenges :

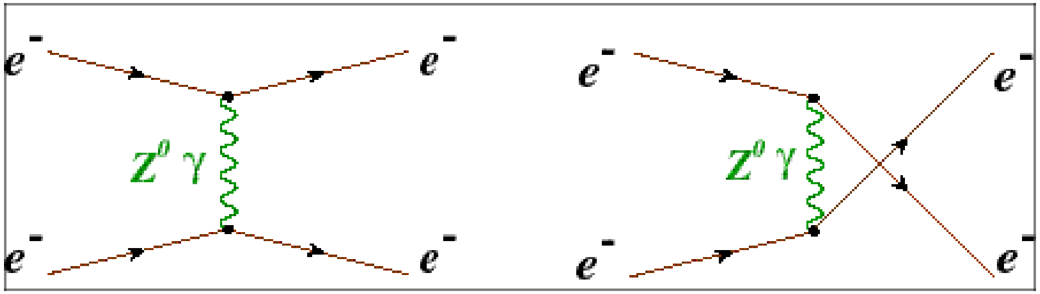
- Statistics
  - High rate, beam polarization, beam current, high-power target, large acceptance detectors
- Noise
  - Electronics, target density fluctuations, detector resolution
- Systematics
  - Helicity-correlated beam asymmetry (false asym.), backgrounds, precision beam polarimetry, precise Q^2 determination



Precision vs smaller asymmetry

PV in Møller Scattering

A Search for New Physics at the TeV Scale



Proposed MOLLER experiment will be the best contact interaction search for leptons at low OR high energy

- Best current limit on contact interaction scales available from LEP2
  - LEP2 only sensitive to parity conserving quantities (g^2_{RL} and $g^2_{RR}+g^2_{LL}$)

Where $g_{ij}=g^*_{ij}$ are contact interaction coupling constants for chirality projections of the electron spinor

- Model independent mass scale for parity violating interactions :

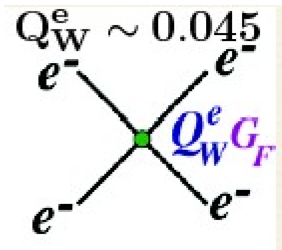
$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g^2_{ij}}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \qquad \frac{\Lambda}{(g^2_{RR} - g^2_{LL})} = 7.5 \text{ TeV}$$

The MOLLER measurement will extend the current sensitivity of 4-electron contact interactions,both qualitatively and quantitatively

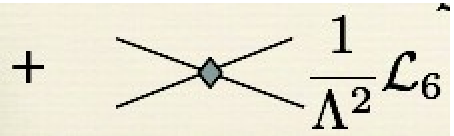
PV in Møller Scattering

A Search for New Physics at the TeV Scale

- Measure weak charge of electron precisely



$$\frac{\delta Q_W^e}{Q_W^e} = 2.4\% \rightarrow A_{new} \sim 0.001 \cdot G_F$$



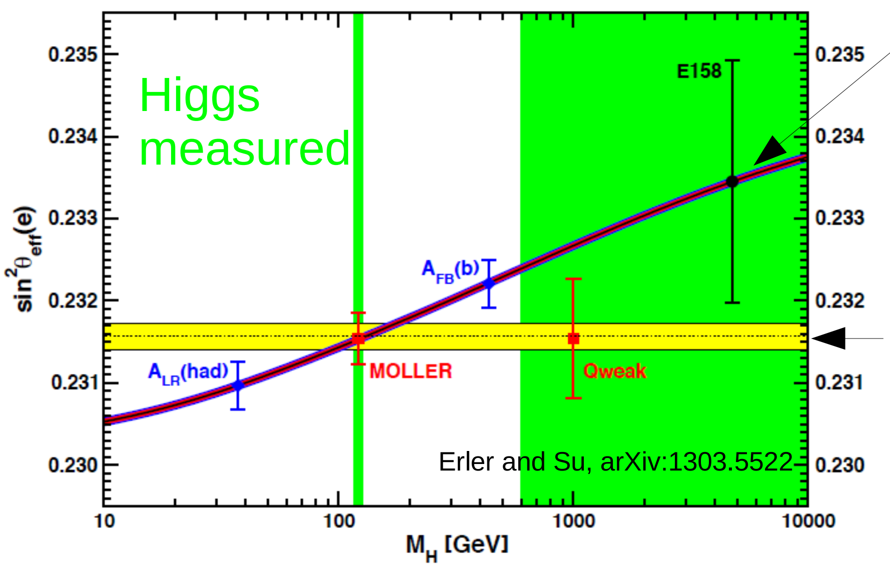
  - Unprecedented sensitivity

$$\frac{\Lambda}{\sqrt{(g_{RR}^2 - g_{LL}^2)}} = 7.5 \text{ TeV}$$

- Provide best projected uncertainty weak mixing angle at any energy scale

$$\delta \sin^2\theta_W = \pm 0.00024 \text{ (stat.)} \pm 0.00013 \text{ (syst.)} \rightarrow \sim 0.1\%$$

use standard model electroweak radiative corrections to evolve best measurements of $\sin^2\theta_W$ to Q ~ MZ

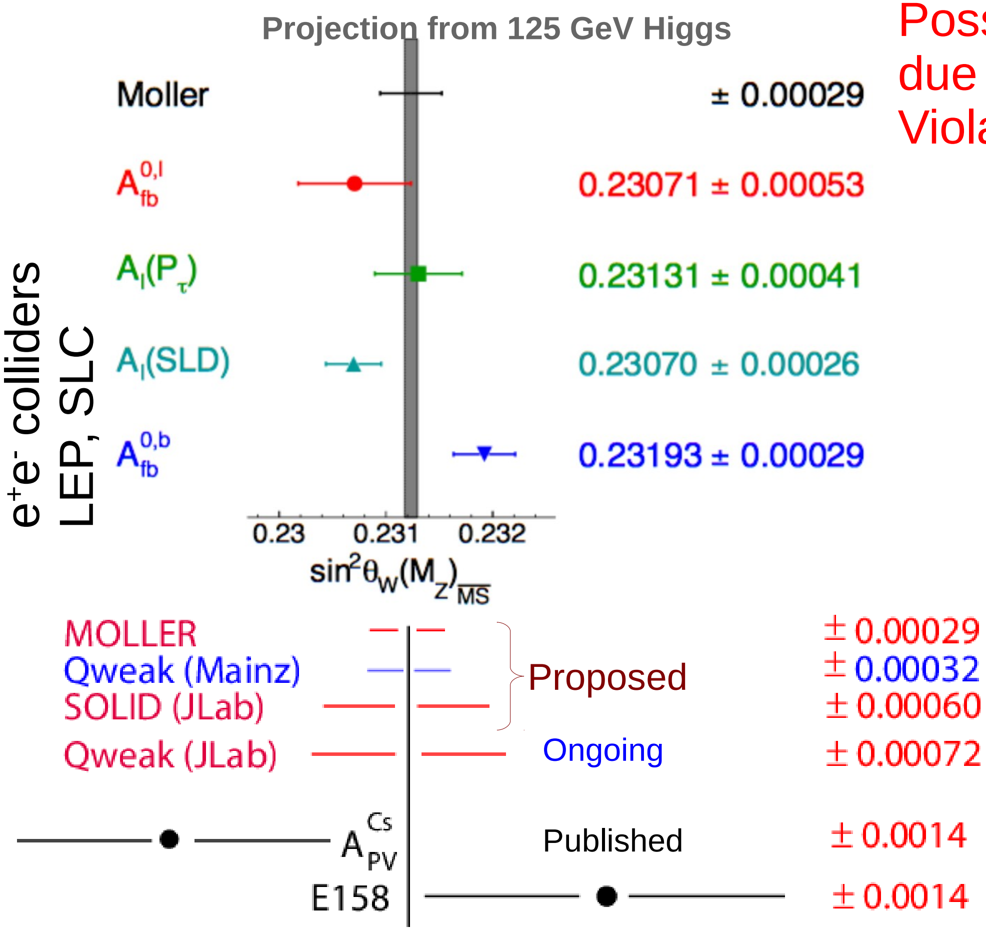


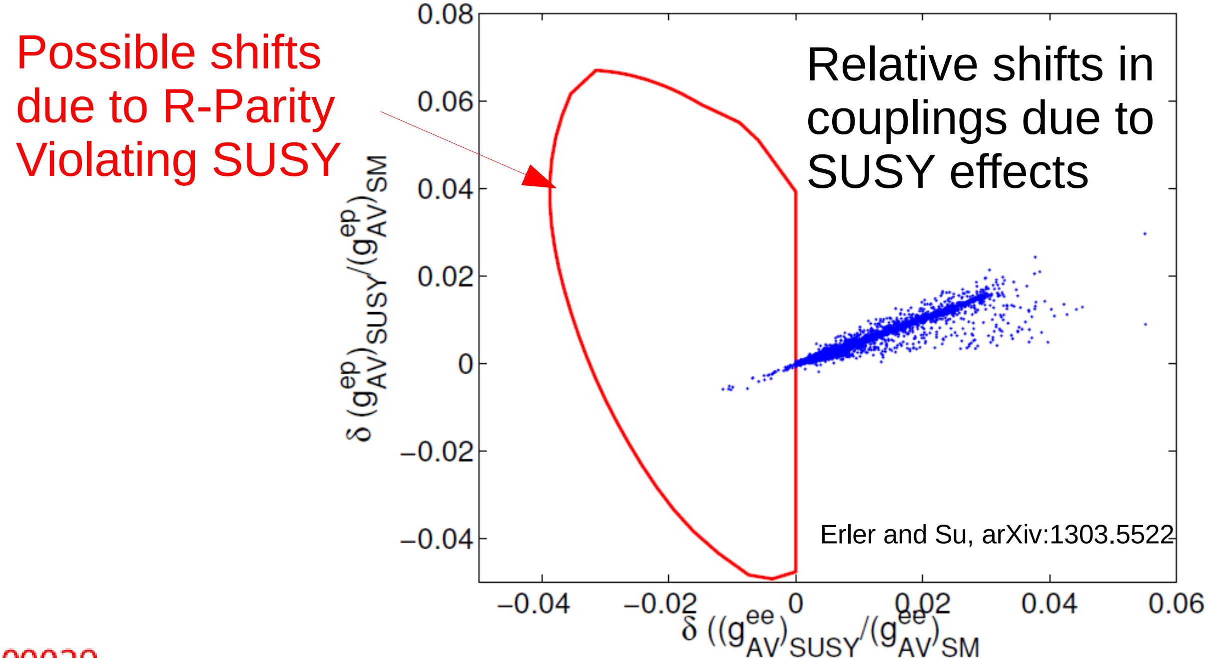
The most precise low energy determination

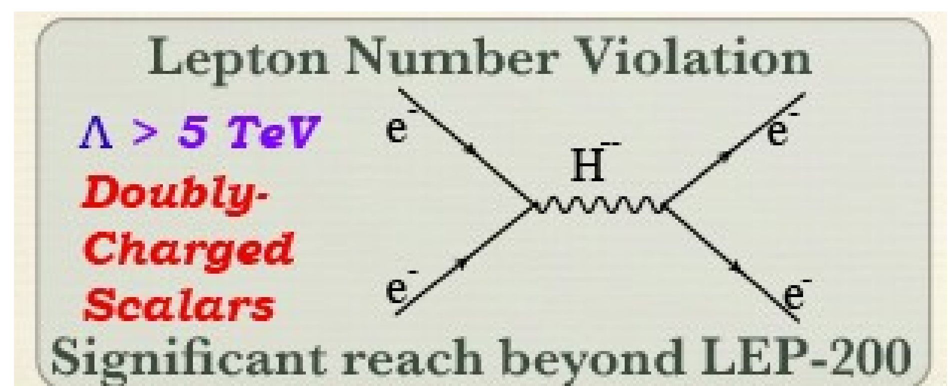
Based on LHC Higgs mass and few other parameters

New Physics beyond SM

Weak mixing angle world data
and future reach from PVES

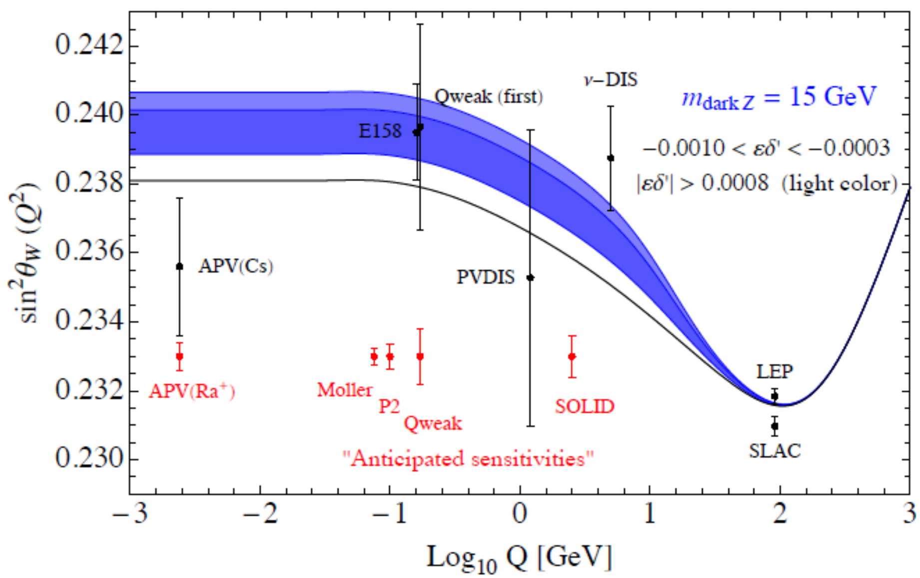


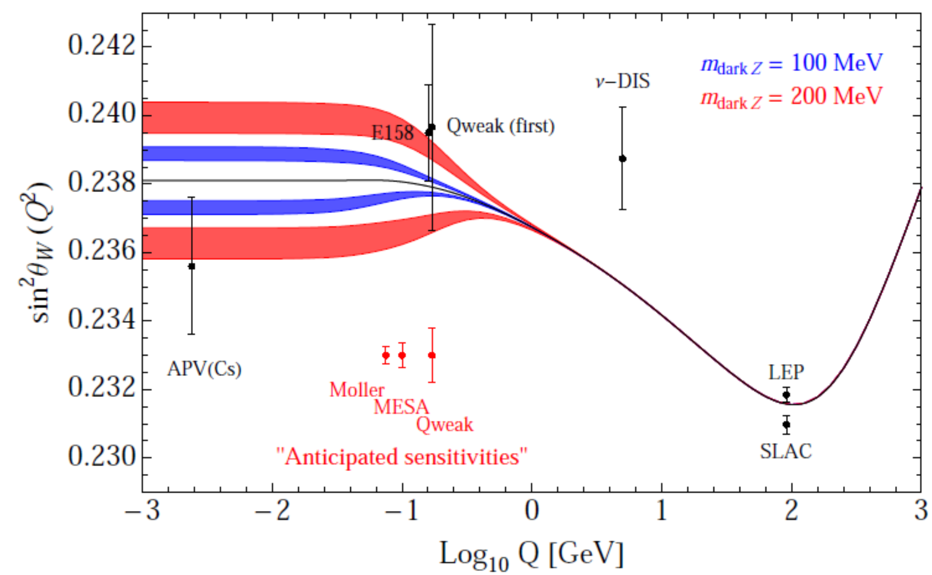




New Physics beyond SM

Dark Z to invisible Particles



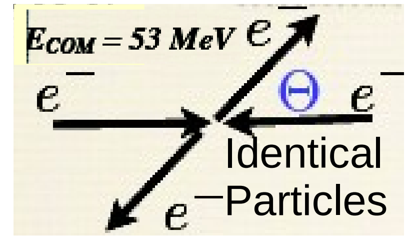


Davoudiasl et. al. arXiv: 1507.00352v2 and 1402.3620

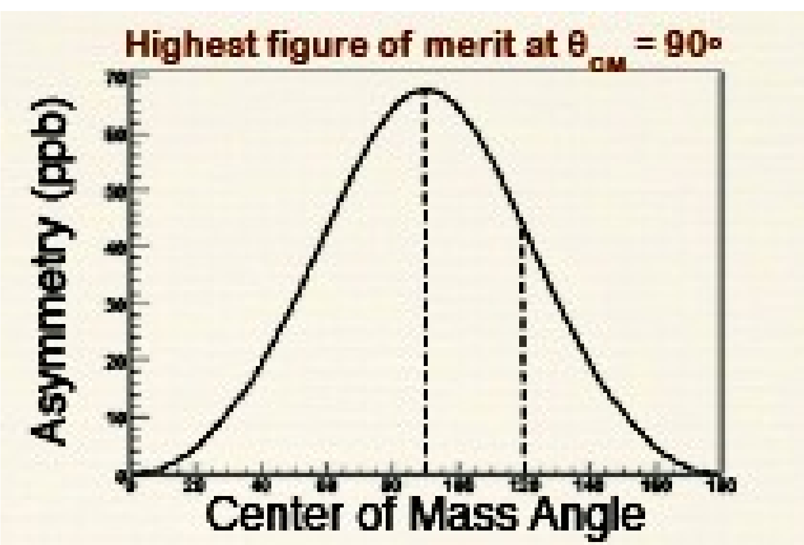
- Dark Z boson at low masses
- Effect will be dependent on the mass of the dark Z
- MOLLER will offer an excellent opportunity to constrain such dark matter interaction
  - Observe such dark Z boson as a shift in the weak mixing angle value

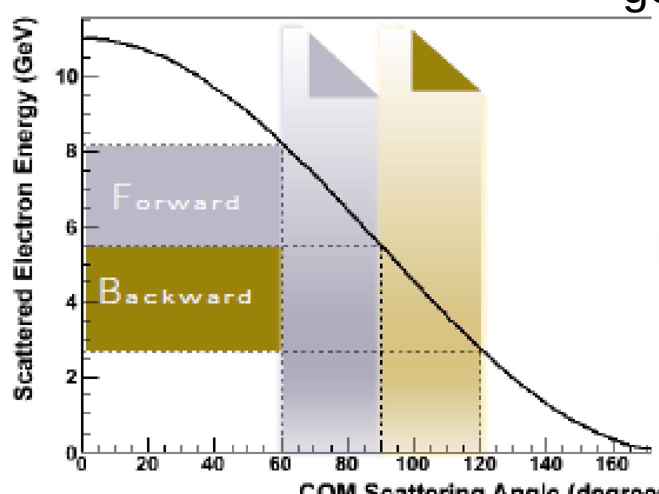
MOLLER Kinematics and Acceptance

- In Møller scattering back and forward scattered electrons can be detected

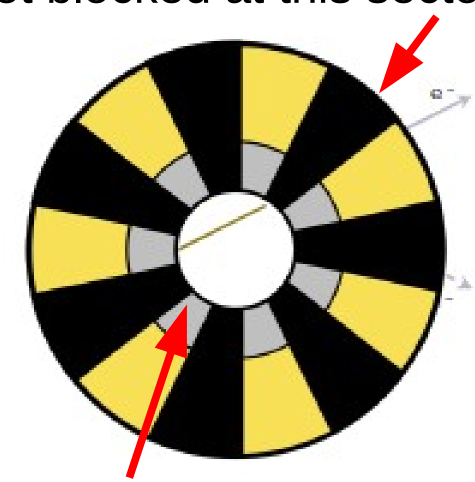


- With odd number of sectors in an unique design, MOLLER experiment gets 100% acceptance



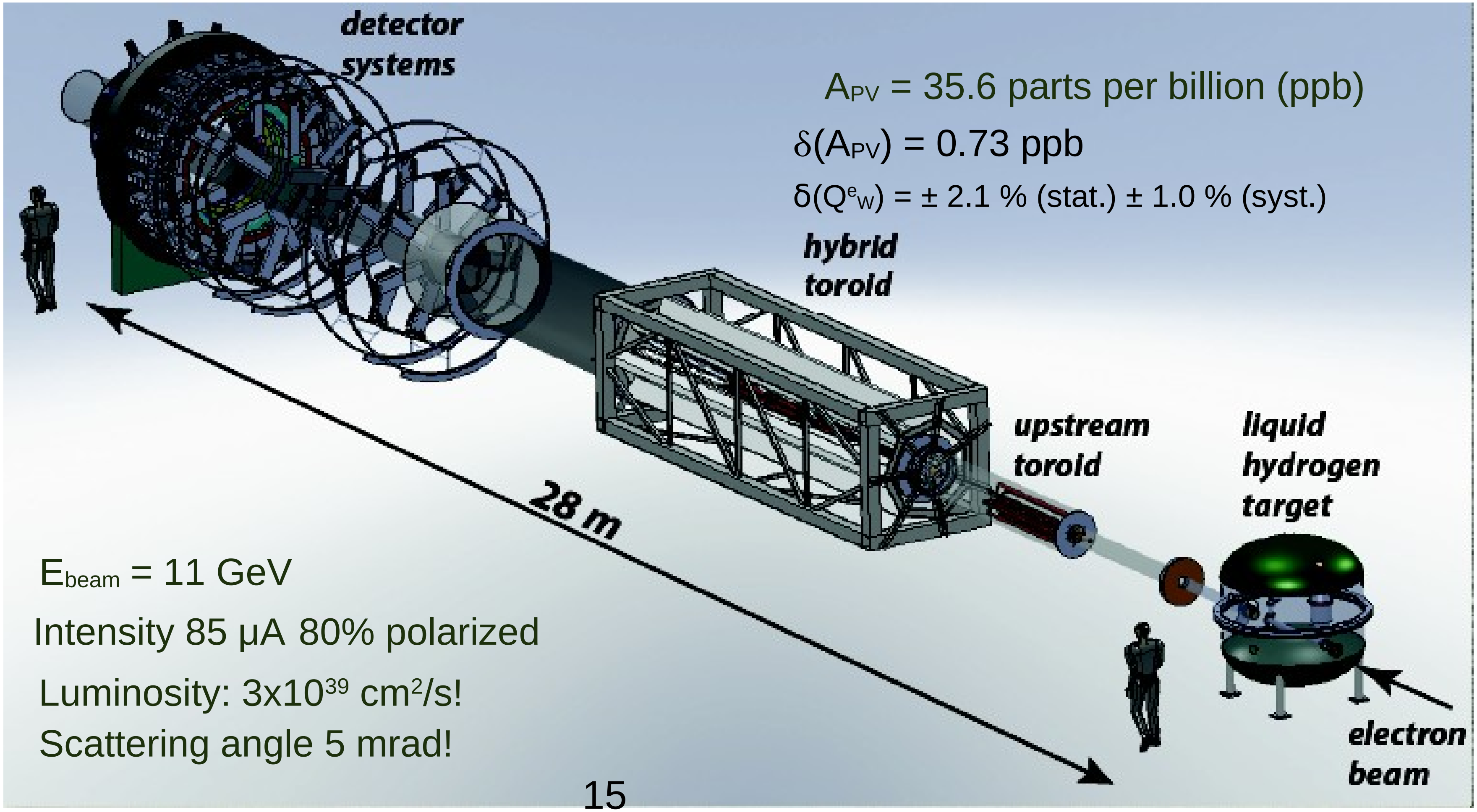


Electrons of θ_{CM} [90,120] that get blocked at this sector ...



… are collected as θ_{CM} [60,90] at this sector

MOLLER Apparatus



A_{PV} = 35.6 parts per billion (ppb)

$\delta(A_{PV})$ = 0.73 ppb

$\delta(Q^e_W)$ = ± 2.1 % (stat.) ± 1.0 % (syst.)

E_{beam} = 11 GeV

Intensity 85 μA 80% polarized

Luminosity: 3×10^{39} cm^2/s!

Scattering angle 5 mrad!

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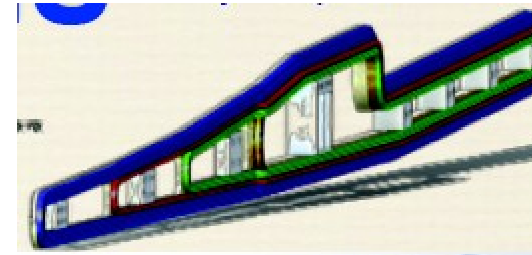
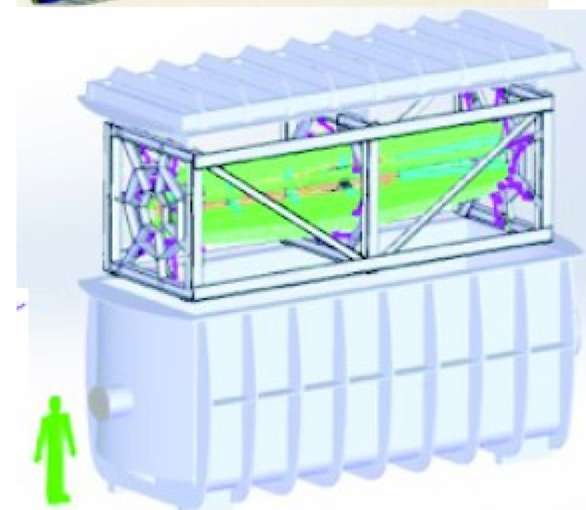
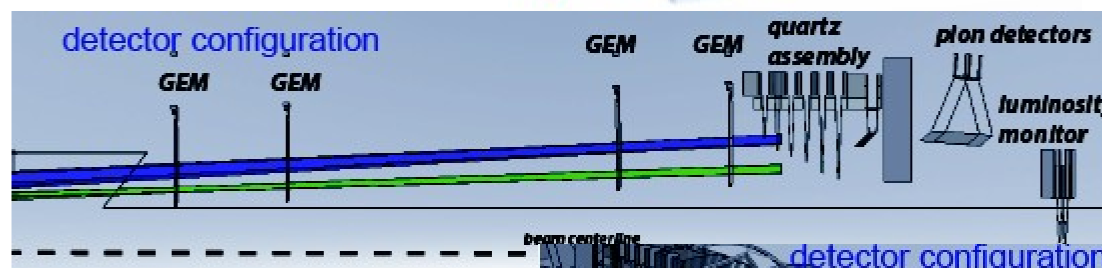
MOLLER Appararus

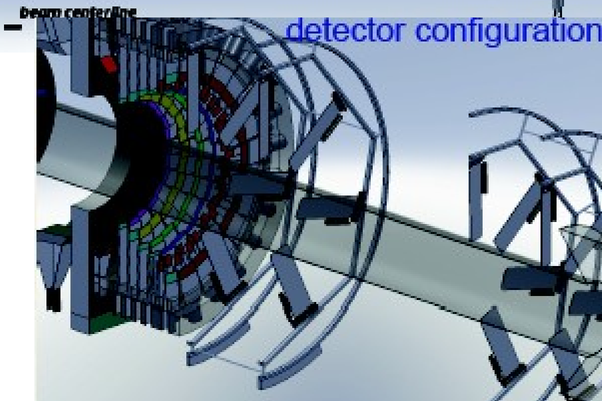
Technical Challenges

- High (150 GHz) scattered electron rate
- High luminosity
  - 1.5 m : 5 KW at 85 uA
- Complete azimuthal acceptance at θ_{lab} of 5 mrad
  - pair of toroidal spectrometers
  - Hightly segmented integrating detectors
- Redundant 0.4 % level beam polarimetry

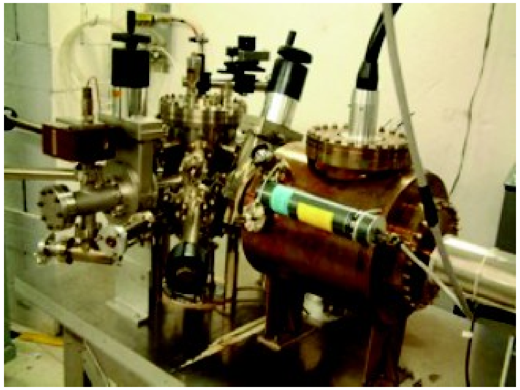






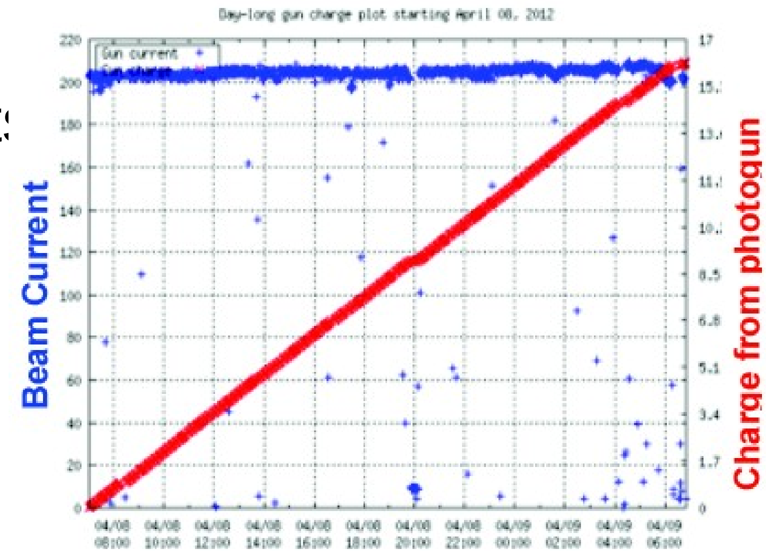


Polarized Electron Source



Electron Gun Requirements

- Ultrahigh vacuum
- No field emission
- Maintenance free



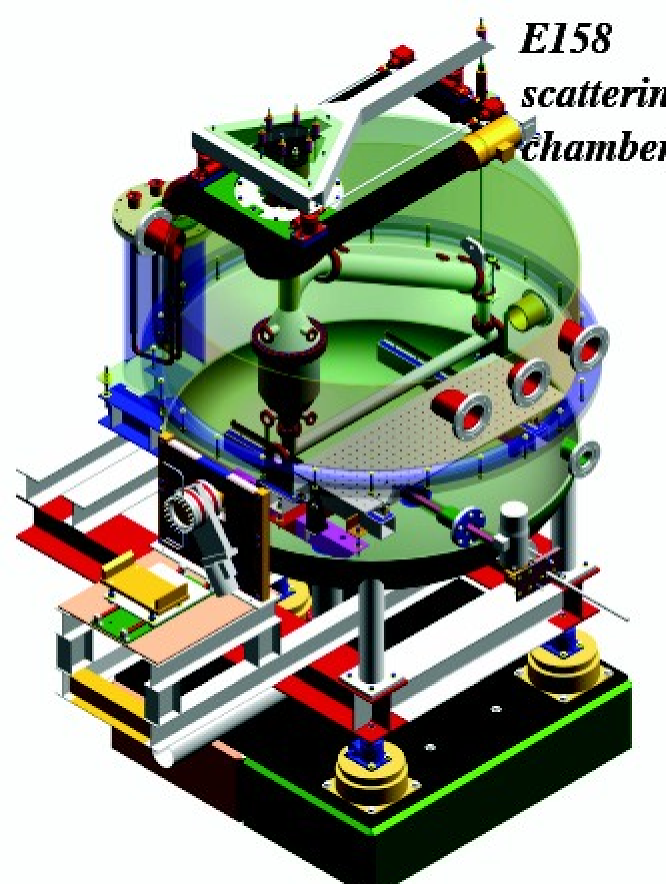
Record performance of 180 uA at 89% pol. (2012)

- Beam helicity is reversed at a pseudo-random pattern
- Sequences of helicity window multiplets will be used to compute the asymmetry
  - MOLLER will use 2 kHz reversal rate

Liquid Hydrogen Target

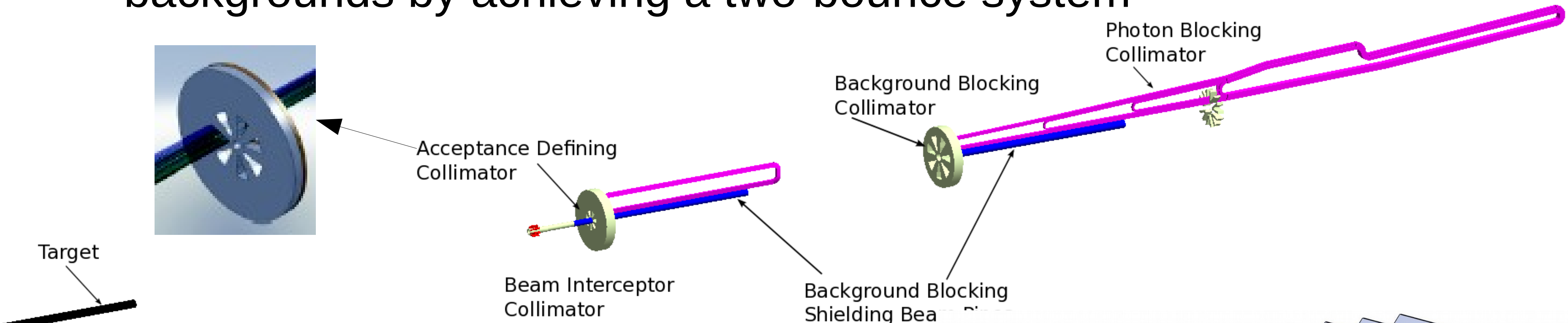
- Need as much thickness as technically possible with least radiative losses
  - Trade-off between counting statistics and systematic effects
- Default design will be from the previous generation MOLLER experiment (E158)

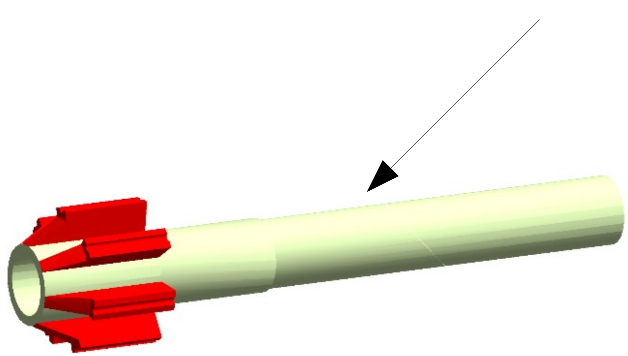
parameter	value
length	*150 cm*
thickness	*10.7 gm/cm²*
X_0	*17.5%*
p,T	*35 psia, 20K*
power	*5000 W*

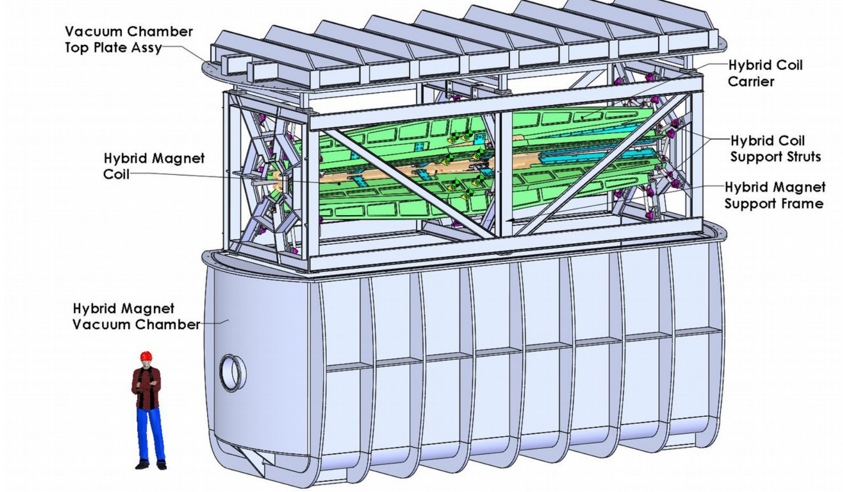


Toroidal Spectrometer

- Provides full azimuthal acceptance
- Have water cooled warm copper coils
- The collimators define the acceptance of the experiment
- Strategic placement of collimators will minimize soft photon backgrounds by achieving a two-bounce system



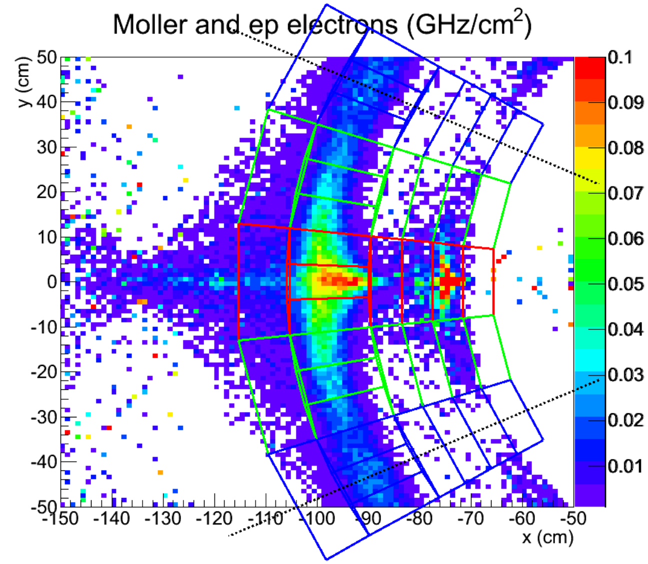


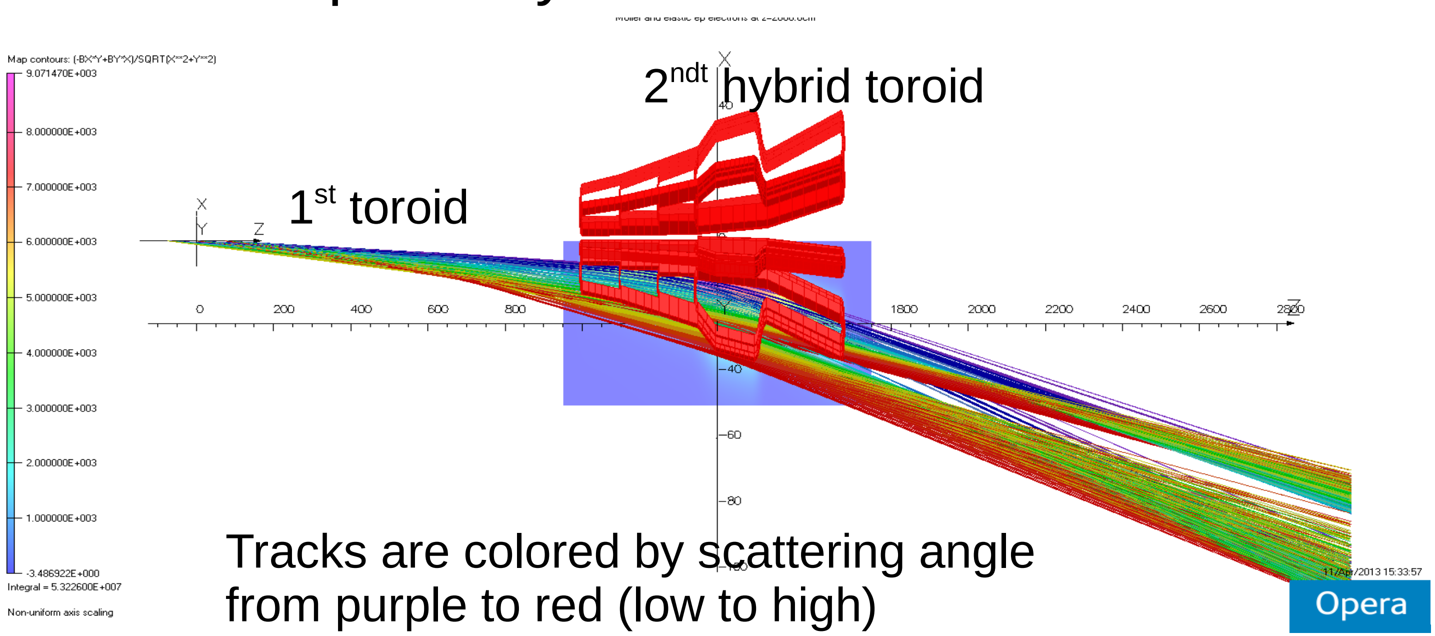


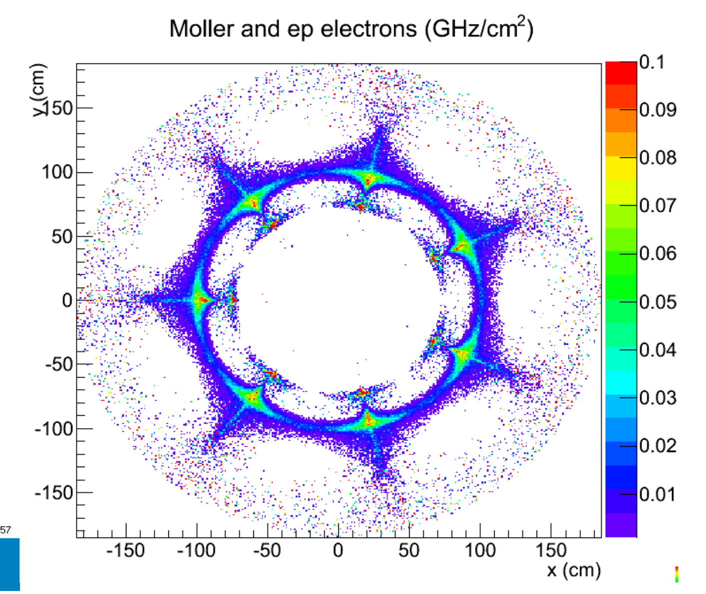
MOLLER Hybrid Magnet and Vacuum Chamber Assembly

Toroidal Spectrometer

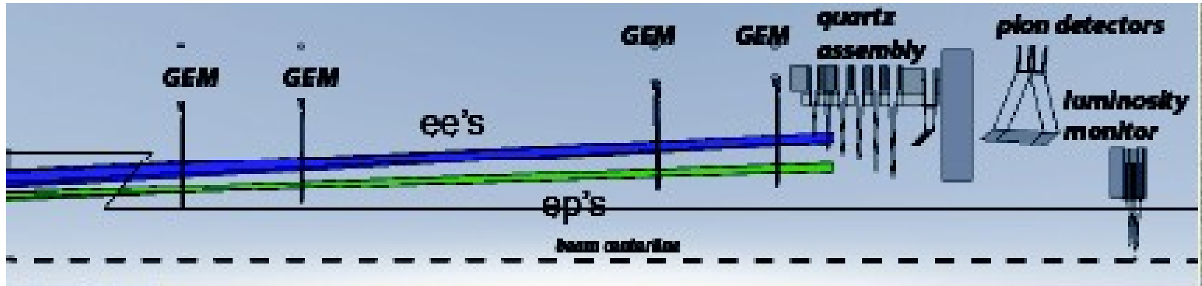
- Møller and ep scattering signals are separated at the detector plane
- Optics are still being fine tuned,
  - Reduce backgrounds
  - Optimize the asymmetry
  - Improve symmetric forward/backward



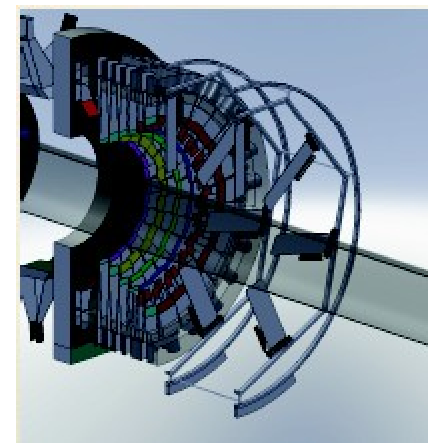


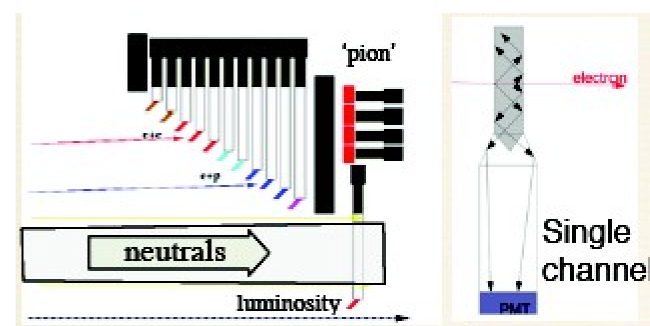


Integrating Detectors Overview

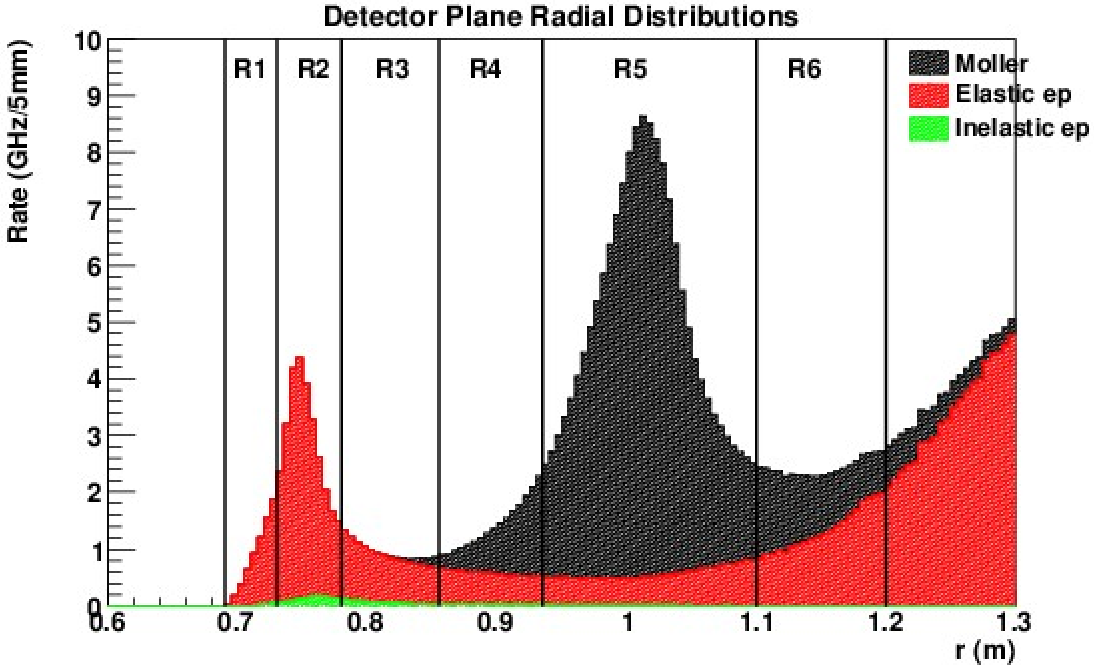


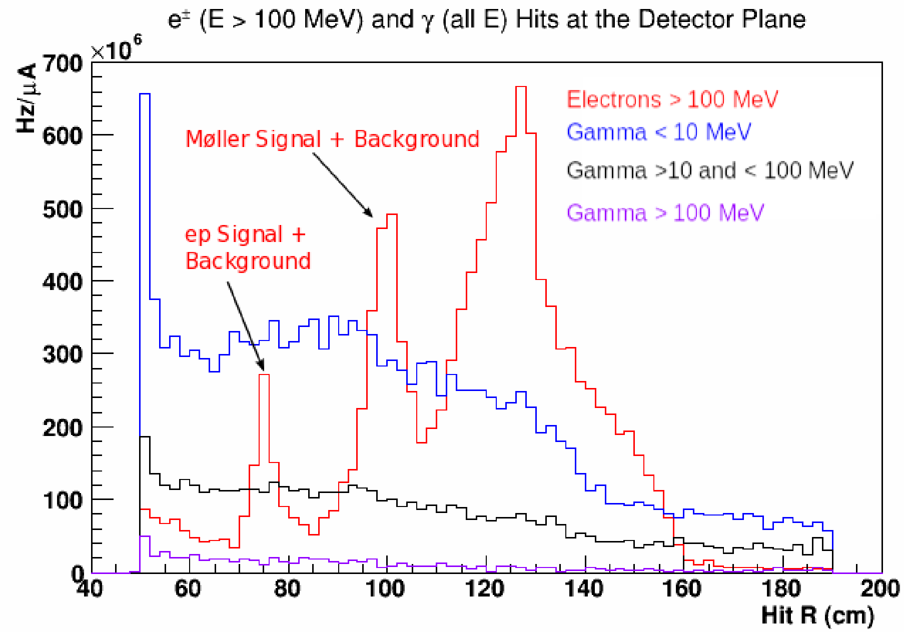
- Detectors are radially and azimuthally segmented
- For detecting Møller and e-p electrons,
  - Quartz with air light guide and PMTs
- For Pions and Muons
  - A calorimeter style detector behind a shielding wall
- Beam and target fluctuations
  - Luminosity monitors





MOLLER Backgrounds





- The primary irreducible backgrounds : ep elastic and inelastic scattering
- Other background sources
  - Photons and neutrons from 2 bounce collimation system
  - Pions and muons : photo-production and DIS

Statistics and Systematics Errors

Beam Property	Assumed Sensitivity	Accuracy of Correction	Required 2 kHz random fluctuations	Required cumulative helicity-correlation	Systematic contribution
Intensity	1 ppb / ppb	$\sim$1%	$<$ 1000 ppm	$<$ 10 ppb	$\sim$ 0.1 ppb
Energy	-1.4 ppb / ppb	$\sim$10%	$<$ 108 ppm	$<$ 0.7 ppb	$\sim$ 0.05 ppb
Position	0.85 ppb / nm	$\sim$10%	$<$ 47 μm	$<$ 1.2 nm	$\sim$ 0.05 ppb
Angle	8.5 ppb / nrad	$\sim$10%	$<$ 4.7 μrad	$<$ 0.12 nrad	$\sim$ 0.05 ppb

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Total systematic	**1.1**

All systematics required at sub-1% level

MOLLER Workforce Outlook

- Majority of PVES (Qweak and PREX) collaborators are committed to MOLLER
- Estimate 12-15 post-docs FTEs and 25 PhD students at the peak!
- Funding from DOE (NP), NSF and NSERC (Canada)
  - Majority of user funding would be redirected towards MOLLER from existing grants
  - Expecting new foreign participation

Summary and Outlook

- Best contact interaction reach for leptons at any energy
  - Similar to LHC reach with semi-leptonic amplitudes
  - To do better for a 4-lepton contact interaction would require:
    - Giga-Z factory, linear collider, neutrino factory or muon collider
- The unique discovery capability in MOLLER will be very important
  - If LHC sees any anomaly in runs 2 and 3 (~ 2022)
- MOLLER also provides discovery scenarios beyond LHC signatures
  - Hidden weak scales
  - Lepton number violating interactions
  - Light dark matter mediators
- Modular experiment design enable multiple runs
  - Allows other experiments to come to the floor between MOLLER runs
  - Design will allow modest time for deinstallation/installation
- Commissioning and first physics run would yield major results

Supplementary

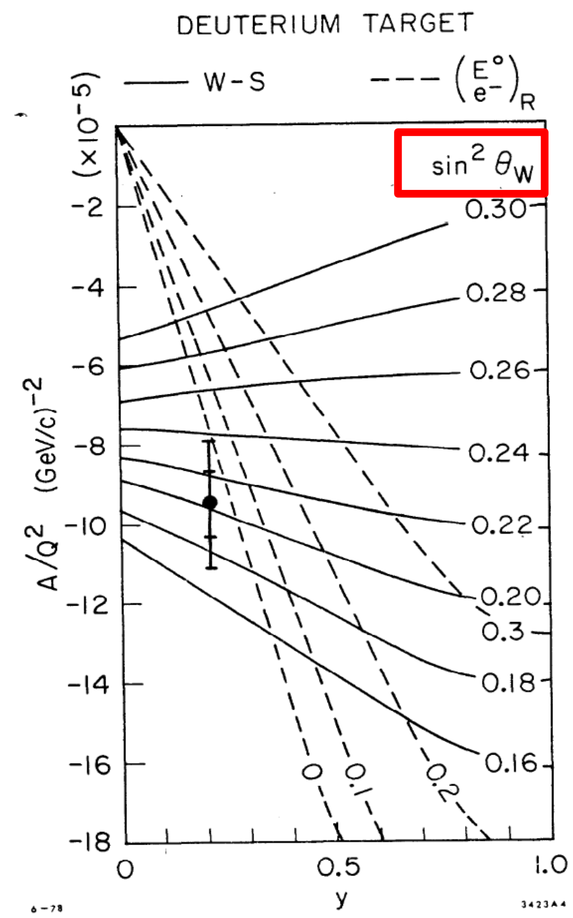
PVES Historical Significance

- Confirmation of the EW SM from the first PVES experiment at SLAC by Prescott et. al.
- First measurement of parity-violation in the neutral weak current!
  - Measured the weak mixing angle to be around ¼: A small axial vector(e) **X** vector(f) weak neutral interaction!

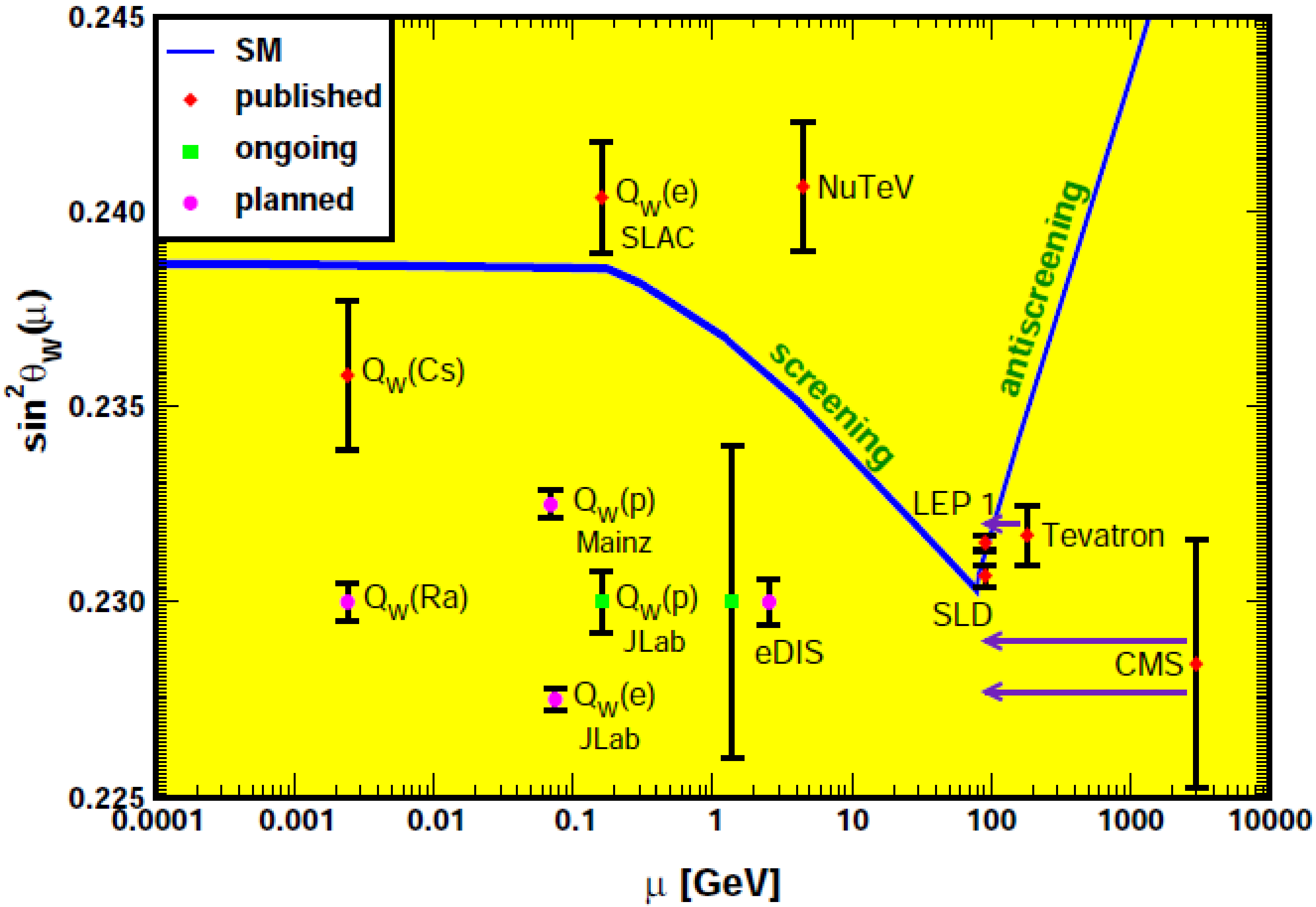
$$\mathrm{U(1)_Y} \rightarrow \mathrm{B}_\mu$$

$$\mathrm{SU(2)_L} \rightarrow \mathrm{W}^1_\mu,\ \mathrm{W}^2_\mu,\ \mathrm{W}^3_\mu$$

$$\begin{pmatrix} \mathrm{A}_\mu \\ \mathrm{Z}_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_\mathrm{W} & \sin\theta_\mathrm{W} \\ -\sin\theta_\mathrm{W} & \cos\theta_\mathrm{W} \end{pmatrix} \begin{pmatrix} \mathrm{B}_\mu \\ \mathrm{W}^3_\mu \end{pmatrix}$$



1st PVDIS at SLAC!
first result in 1978:
Prescott et al., PLB 77, 347 (1978)
Prescott et al., PLB 84, 524 (1978)



Running of the weak mixing angle overlapped with the various data points. Source : Erler and Su, arXiv:1303.5522

Polarimetry for MOLLER

- Compton polarimeter
  - High precision continuous measurements
- Møller polarimeter
  - High precision invasive measurements
- Mott polarimeter at the injector
  - Cross check for calibration and absolute normalization
- Upcoming polarimetry measurements
  - High precision operation at 1 GeV (PREX, 1%), 2 GeV (CREX, 0.8%)

MOLLER Auxiliary Measurements

- PV asymmetry in inelastic electron proton scattering
  - Main input to improving box diagram uncertainties of the weak charge of the proton
  - QCD interplay : quark hadron duality
- Transverse asymmetry measurements
  - Møller analyzing power with transverse polarized electron beam : highly sensitive check of the MOLLER apparatus for systematic effects
  - Parasitic measurements of elastic and inelastic electron proton scattering at kinematic regime never measured before
  - Potential opportunity to measure on heavier nuclei

PVES Progress

Looking to Future : Technical challenges :

- Random beam fluctuations limits : present (Qweak) vs. Future (MOLLER)
- Beamline monitor precision : present (Qweak) vs. Future (MOLLER)

Beam property	MOLLER spec.	Qweak observed
Intensity	< 1000 ppm	500 ppm
Energy	< 108 ppm	6.5 ppm
Position	< 47 μm	48 μm
Angle	< 4.7 μrad	1.4 μrad

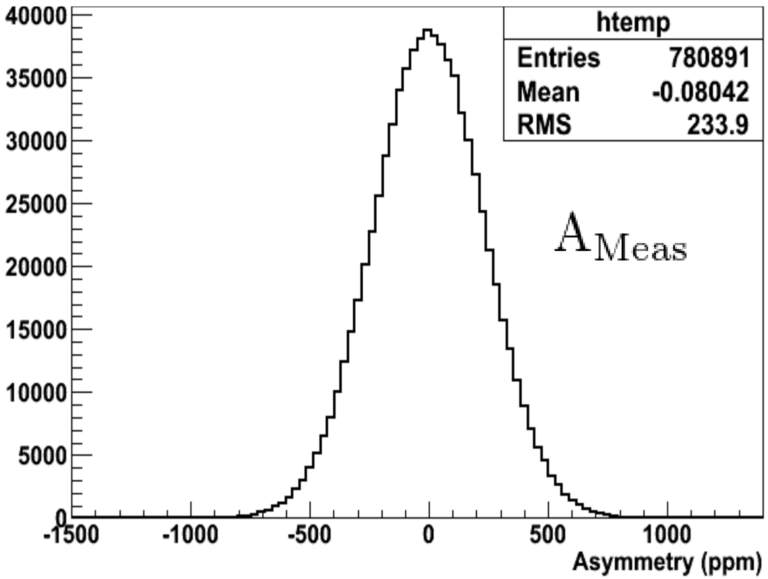
Courtesy of Mark Pitt

Monitor type	MOLLER spec.	Qweak observed
Beam charge	10 ppm	65 ppm
Beam position	3 μm	6 μm

Courtesy of Mark Pitt

How to Do A PVES Experiment

Sample asymmetry distribution



Contribution	Expected σ_A (ppm)
Pure statistics	**201**
Detector resolution	92
Current monitor resolution	50
Target boiling	57
Total	**233.7**

$$A_{Meas} = \frac{V_R - V_L}{V_R + V_L} \rightarrow A_{PV} = \frac{\frac{d\sigma^R}{d\Omega} - \frac{d\sigma^L}{d\Omega}}{\frac{d\sigma^R}{d\Omega} + \frac{d\sigma^L}{d\Omega}}$$

$$\delta A = \frac{\sigma_A}{\sqrt{N_{QRT}}}$$

σ_A = 230-260 ppm

A_{Phys} = -0.200 ppm

To get 3% (δA_{Phys}= 0.006 ppm)

Need about 1 year of running

MOLLER Collaboration

Expression of interest by collaborating institutions

- Polarized source: UVa, JLab, Miss.St.
- Hydrogen Target: JLab, CalState LA, Miss.St.
- Spectrometer Magnets: Canada, ANL, MIT, SBU, UVa
- Focal Plane Detectors: Syracuse, Canada, JLab, UNC A&T, VaTech, SBU
- Luminosity Monitors: VaTech, Ohio
- Pion Detectors: SBU, LATech, UNC A&T
- Tracking Detectors: William & Mary, Canada, SBU, UVa, INFN Roma, MIT
- Electronics: Canada, JLab, UMass
- Beamline Instrumentation: SBU, JLab, VaTech
- Polarimetry: UVa, Syracuse, JLab, CMU, ANL, Miss.St., Clermont-Ferrand, Mainz, William & Mary, Temple
- Data Acquisition: Ohio, Rutgers, JLab
- Simulations: SBU, UMass, Canada, Berkeley, Idaho State, UVa, LaTech