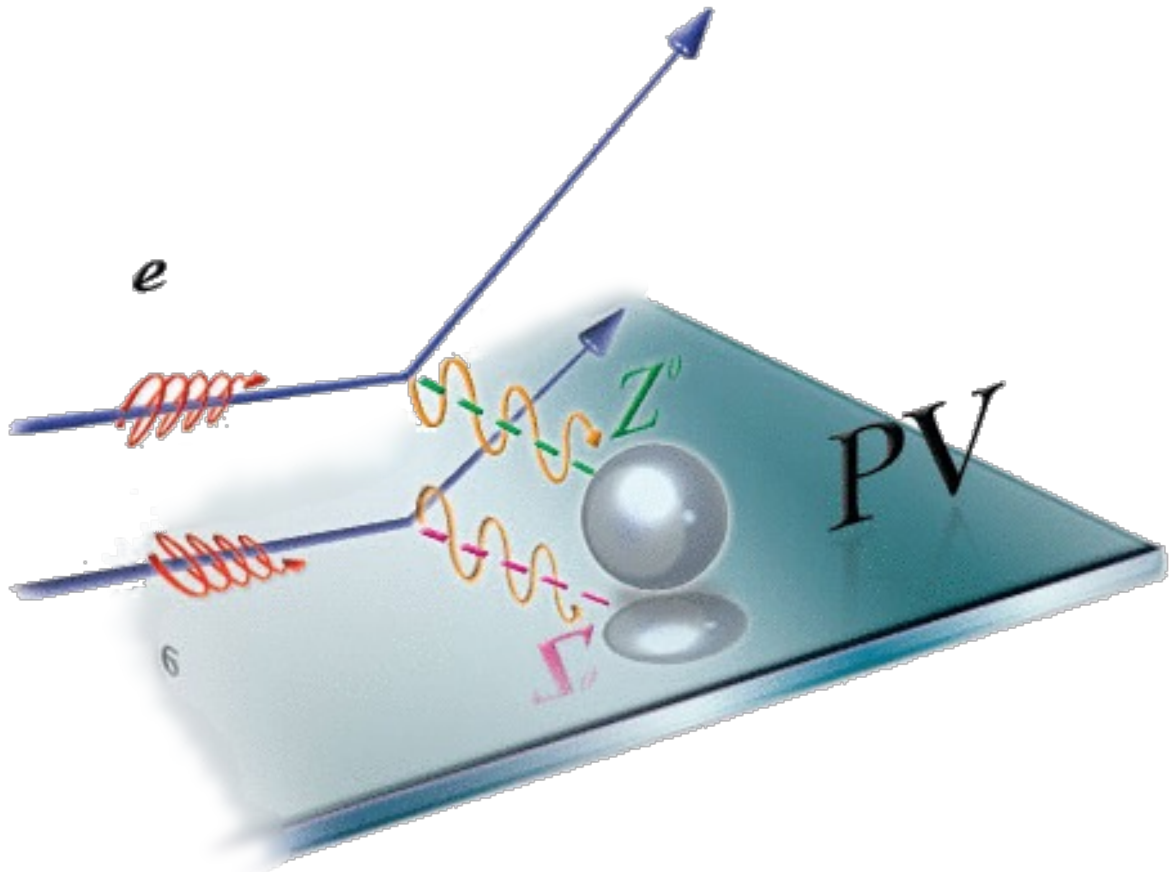
The MOLLER experiment:

Measuring the weak electron-electron interaction

David S. Armstrong



Physics 212
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WILLIAM & MARY CHARTERED 1693
U.S. DEPARTMENT OF ENERGY | Office of Science
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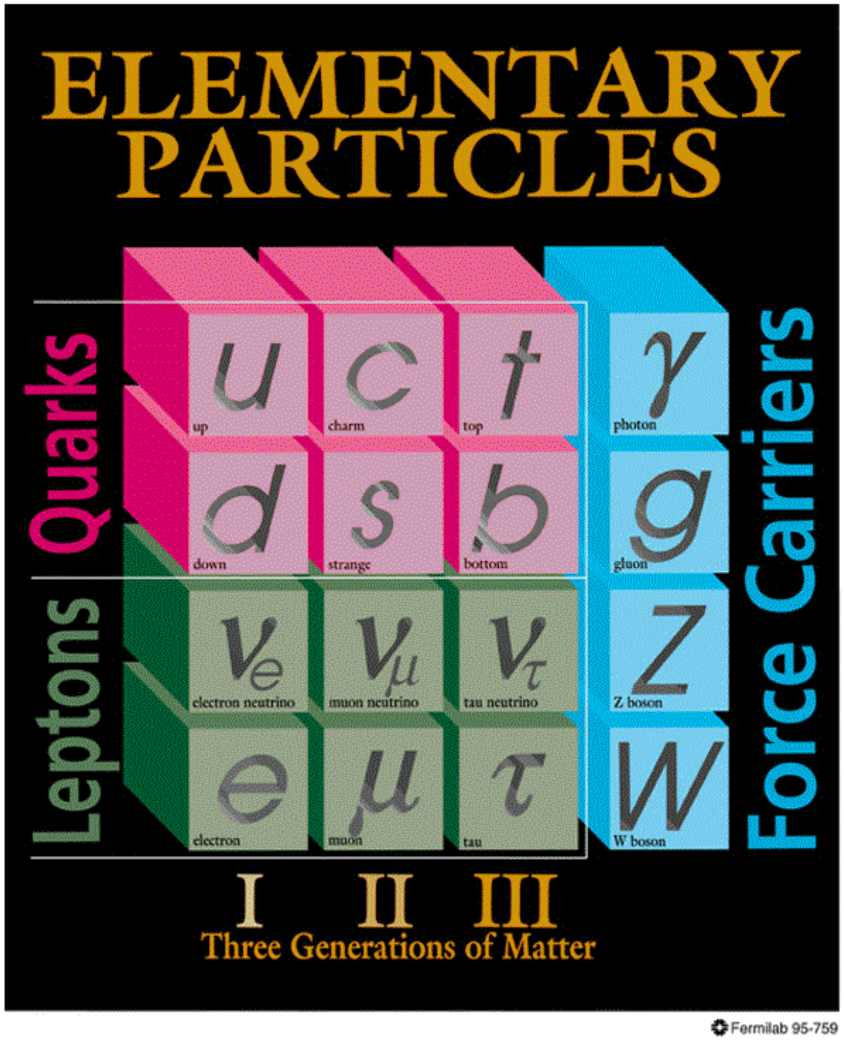
The Standard Model

Our best description of nature's fundamental particles and their interactions



- Building blocks are quarks and leptons

  point-like, spin ½ particles

- Forces mediated by exchange of spin 1 particles:
  - Mostly neutral currents (γ ,Z, gluon)
  - One charged current (W^{+-})
  - One colored current (gluon)

The **Standard Model** is not just building blocks….

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$

It is a rigorous, mathematically consistent theory that makes detailed and precise predictions of many phenomena… and, to date, it has *never had a prediction (convincingly) disproved by experiment!*

The recent discovery of the Higgs Boson at the LHC at CERN (needed for this mathematical consistency) "completes" the Standard Model…

so what is left to study?

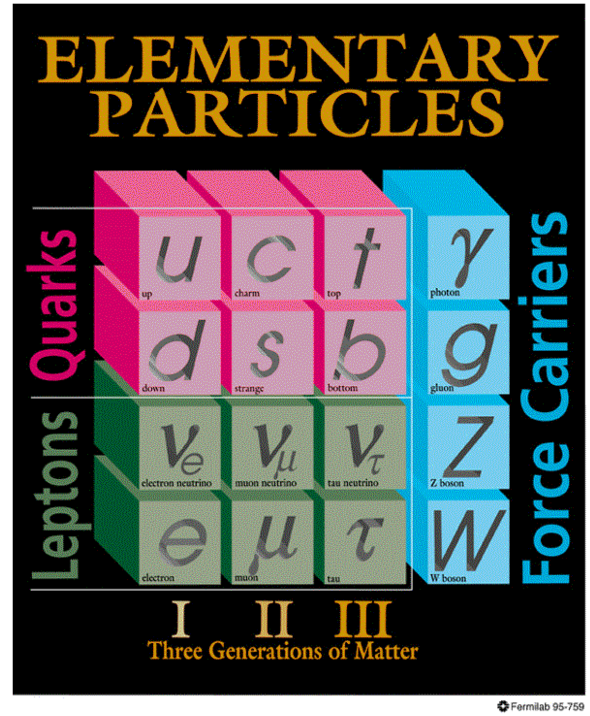
The Standard Model: Issues

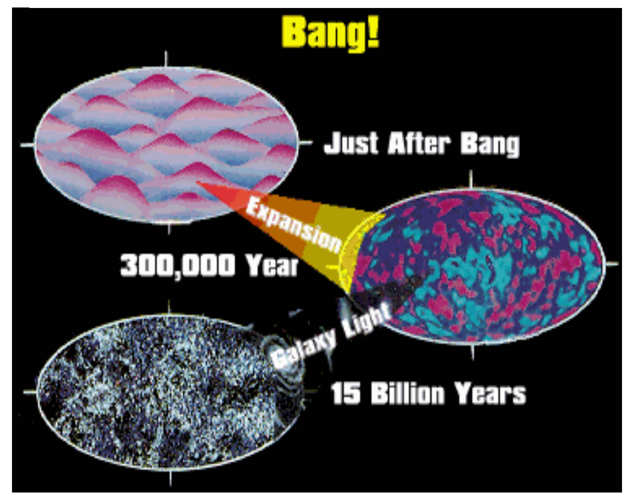
- *Lots* of free parameters:
  masses, mixing angles, and couplings
  (How fundamental is that?)

- Why 3 generations of leptons and quarks?
  (smells like a periodic table…)

- Insufficient CP violation to explain all the matter left over from Big Bang …or we wouldn't be here.

- Doesn't include gravity, dark matter, dark energy
  ooops… gravity determines the structure of our solar system and galaxy; much of the universe seems to be in the form of dark matter and dark energy…





Suggests: Standard Model is only a low-order approximation of reality.
Analogy: Newtonian kinematics is a low-order approximation of Special Relativity.

Precision Tests of the Standard Model

- Received Wisdom: *Standard Model is the effective low-energy theory of underlying more fundamental physics – but how to find & identify this new physics?*

- Finding new physics: Two complementary approaches:
  - Energy Frontier (direct) : *eg*. LHC at CERN
  - Precision Frontier (indirect):

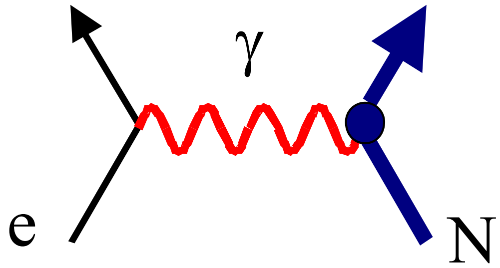
make precision measurement of something that is well-predicted by the Standard Model – see if it is correct.

Here we use the technique: ***Parity-violating electron scattering***

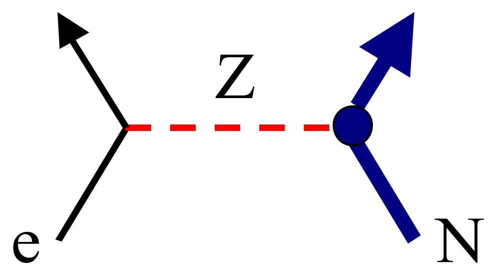
Hallmark of Precision Frontier:

- Choose observables that are *zero* or *suppressed* in Standard Model
- One of these is the "weak charge" of the electron.

Electroweak scattering of electrons



Electron scattering via electromagnetism



Electron scattering via weak interaction

≈10^6 times smaller amplitude at these energies

Final state is *identical* in the two cases…

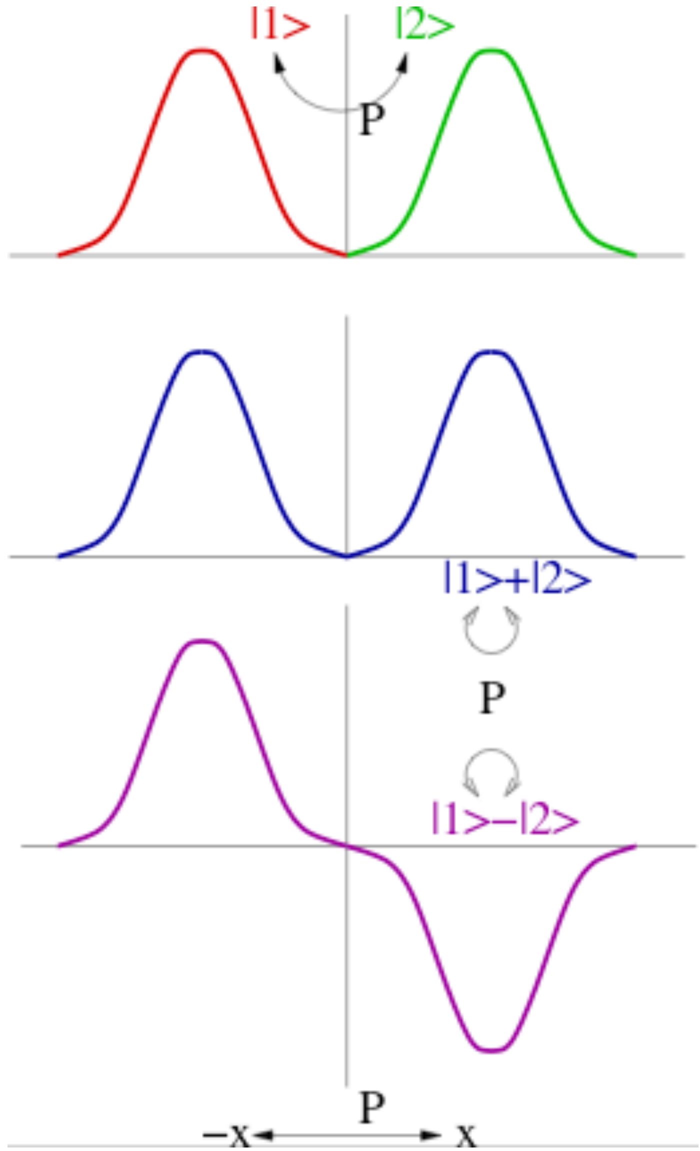
To detect the weak interaction, must exploit parity violation:

The Weak interaction is "left-handed" : it violates parity

(electromagnetism obeys this symmetry)

Right-handed and left-handed electrons scatter
with different probability!

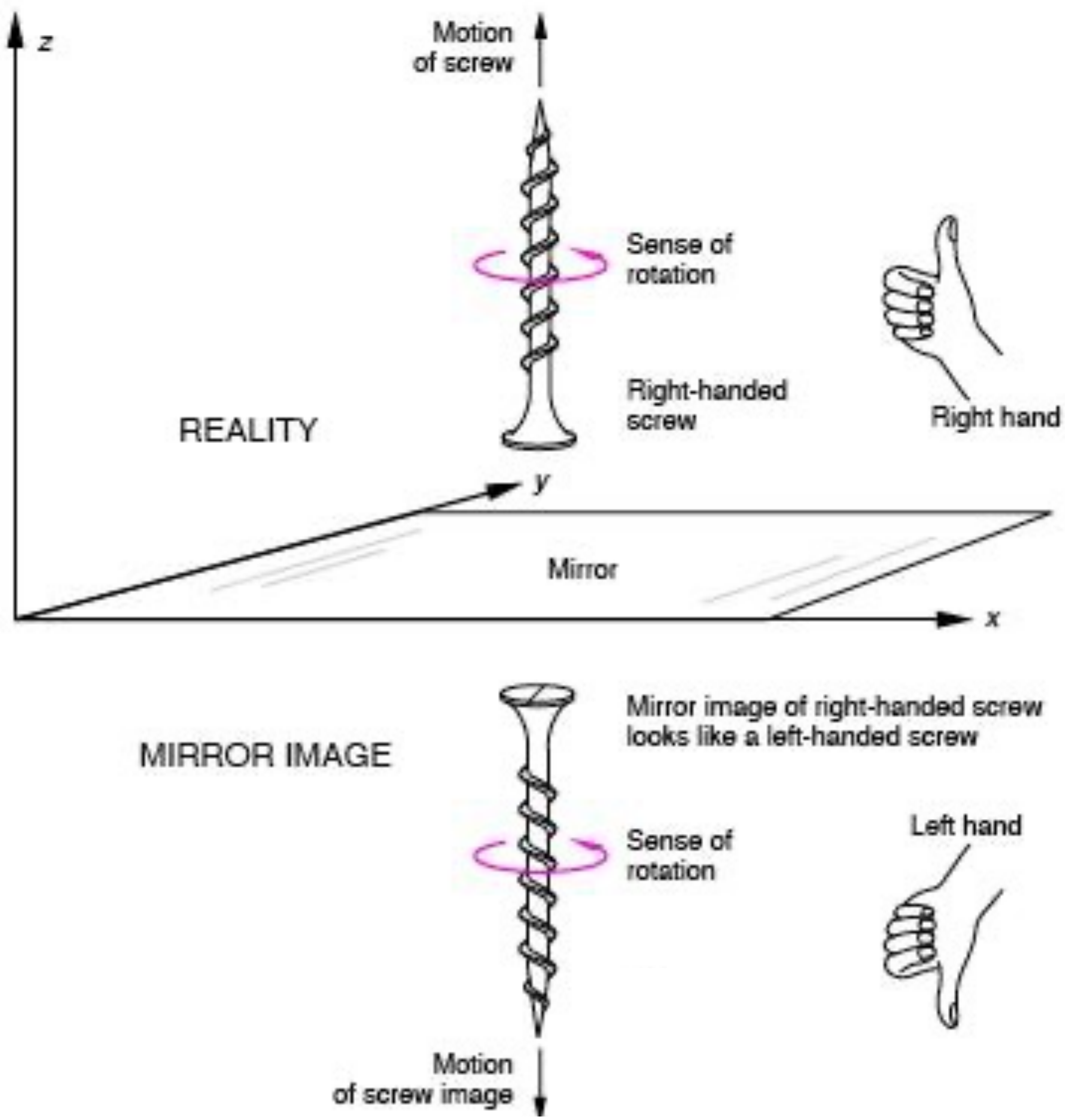
Parity



$$P : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

Parity operation inverts sign of all spatial coordinates

Parity and the Mirror World



Since: **L** = **r** × **p**

r, **p** change sign under parity (vectors)

L does not

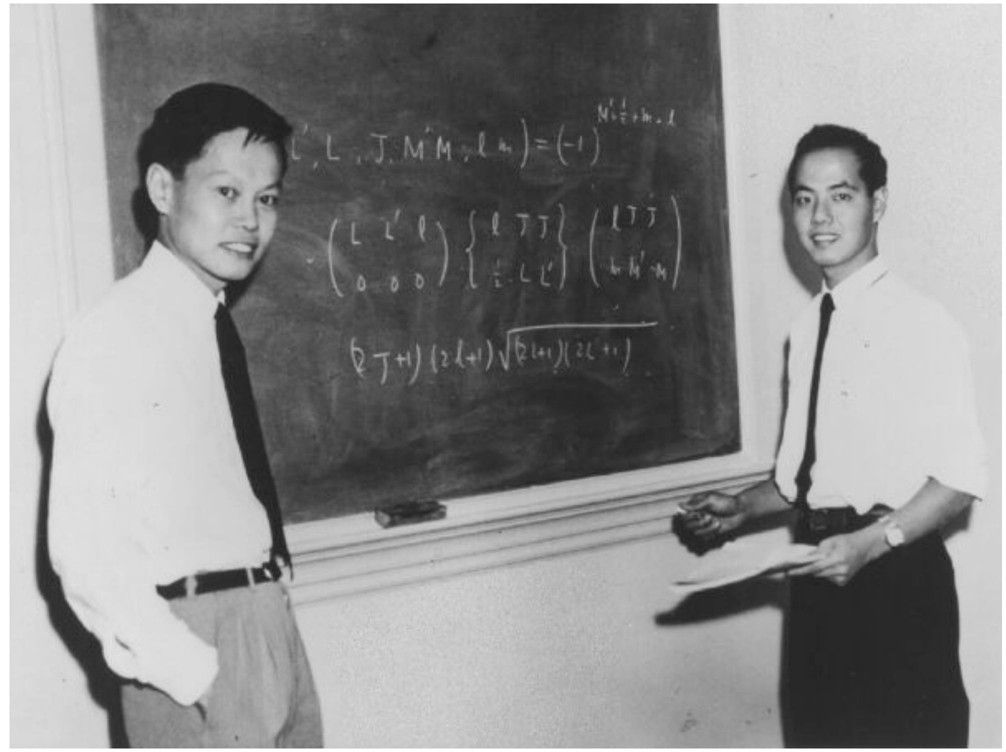
(it's an *axial* vector)

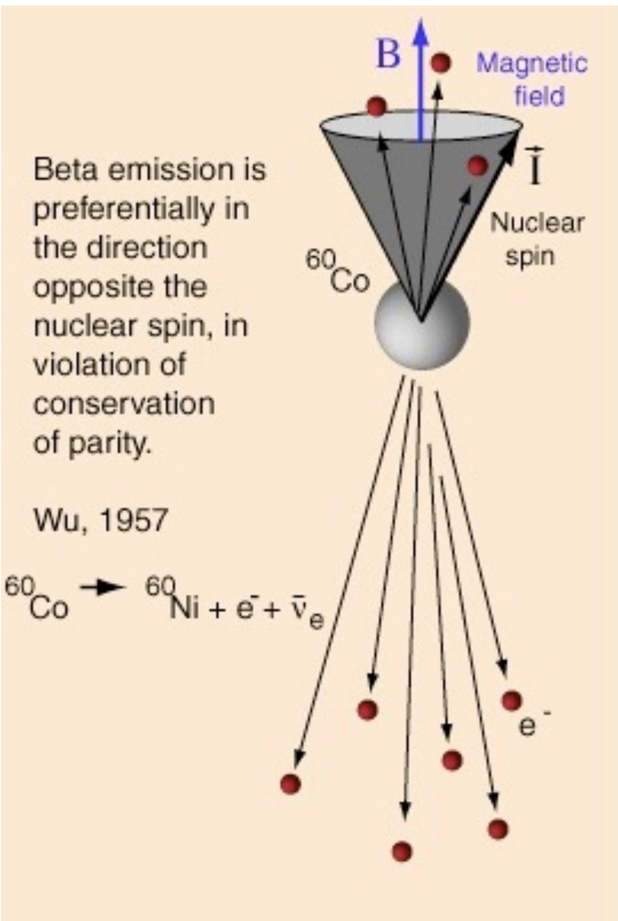
(x → -x and y → -y is same as a 180° rotation around z axis)

Thus: *if* parity symmetry is obeyed, reaction rate can't depend on σ·p
Right and left handed electrons should scatter the same…

Parity Violation in the Weak Interaction

T.D. Lee and C.N. Yang suggested parity violation in the weak interaction (1956)





C.S. Wu and collaborators observed effect in nuclear beta decay later that year

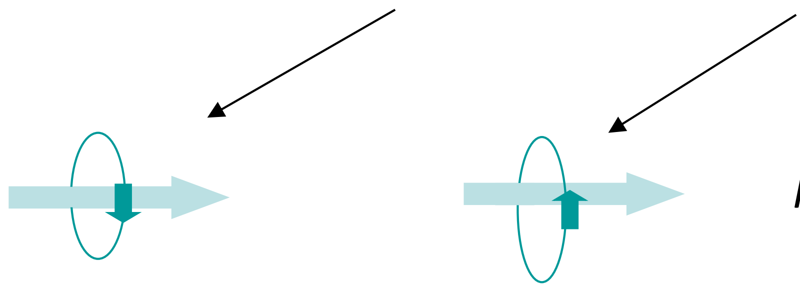
Hmmm….

aside: The reason that the weak interaction violates parity is not known… put in to Standard Model "by hand".

Parity Violation – summary

Electrons spin on their own axes:

either clockwise or counter-clockwise with respect to the direction of their motion: “right-handed” or “left-handed”.



Mirror images!

Parity symmetry says: scattering must behave *same* as in a “mirror world” which interchanges right and left hands.

This is true for electromagnetism, but not for the Weak force

(the universe is not ambidextrous!)

Measure the *difference* in the scattering probability for right-handed and left-handed electrons ⟹ the Weak interaction component

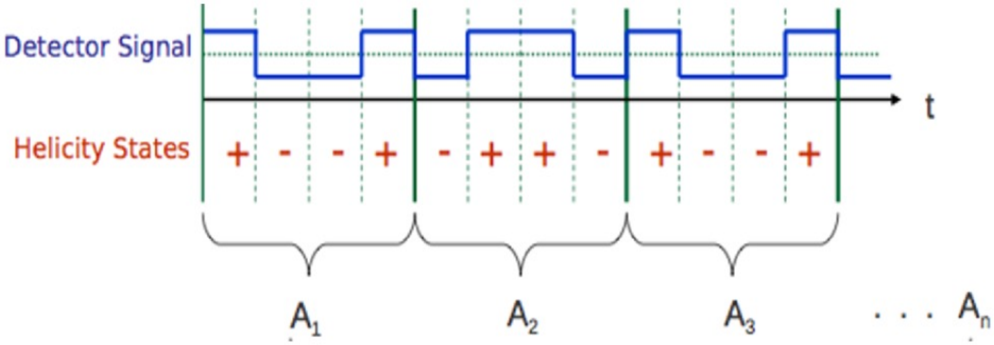
$$\text{Asymmetry} = A = \frac{N^R - N^L}{N^R + N^L}$$

Effect is tiny:

≈ 35 ppb expected

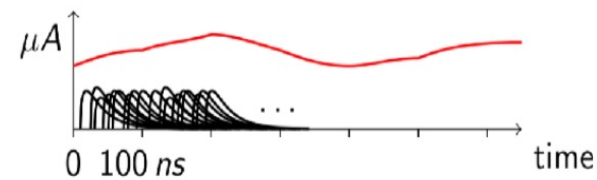
Measuring tiny asymmetries

Rapid (2kHz) helicity reversals



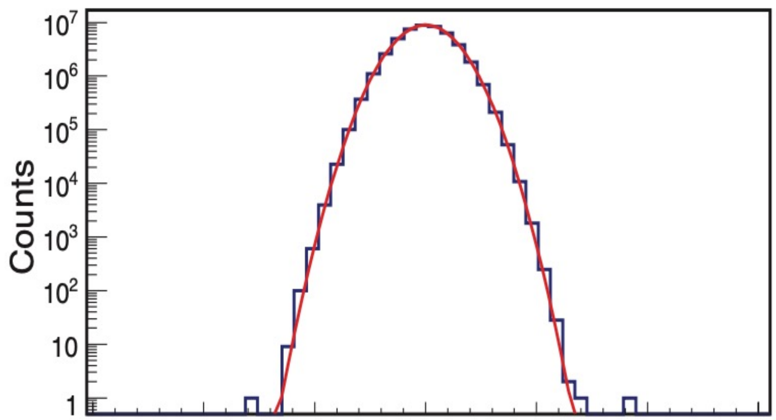
Place a detector where it sees the scattered electron

Analog integrate detector current



Form an asymmetry over the helicity reversal

Measure to 0.01% at 1 kHz, repeat for a year straight



Specialized experimental techniques

- Precise spectrometer to separate signal
- Low noise electronics
- Precise beam control and measurement
- …

Thomas Jefferson National Accelerator Facility: “JLab”

Newport News, Virginia

1980 – initial design

1987 – construction started

1994 – first physics experiments

1995 – design energy (4 GeV)

2000 – 6 GeV achieved

2015 – 12 GeV upgrade

User group: 1500 physicists

Funded by U.S. DOE

Beam currents to 180 μA

JLab Accelerator

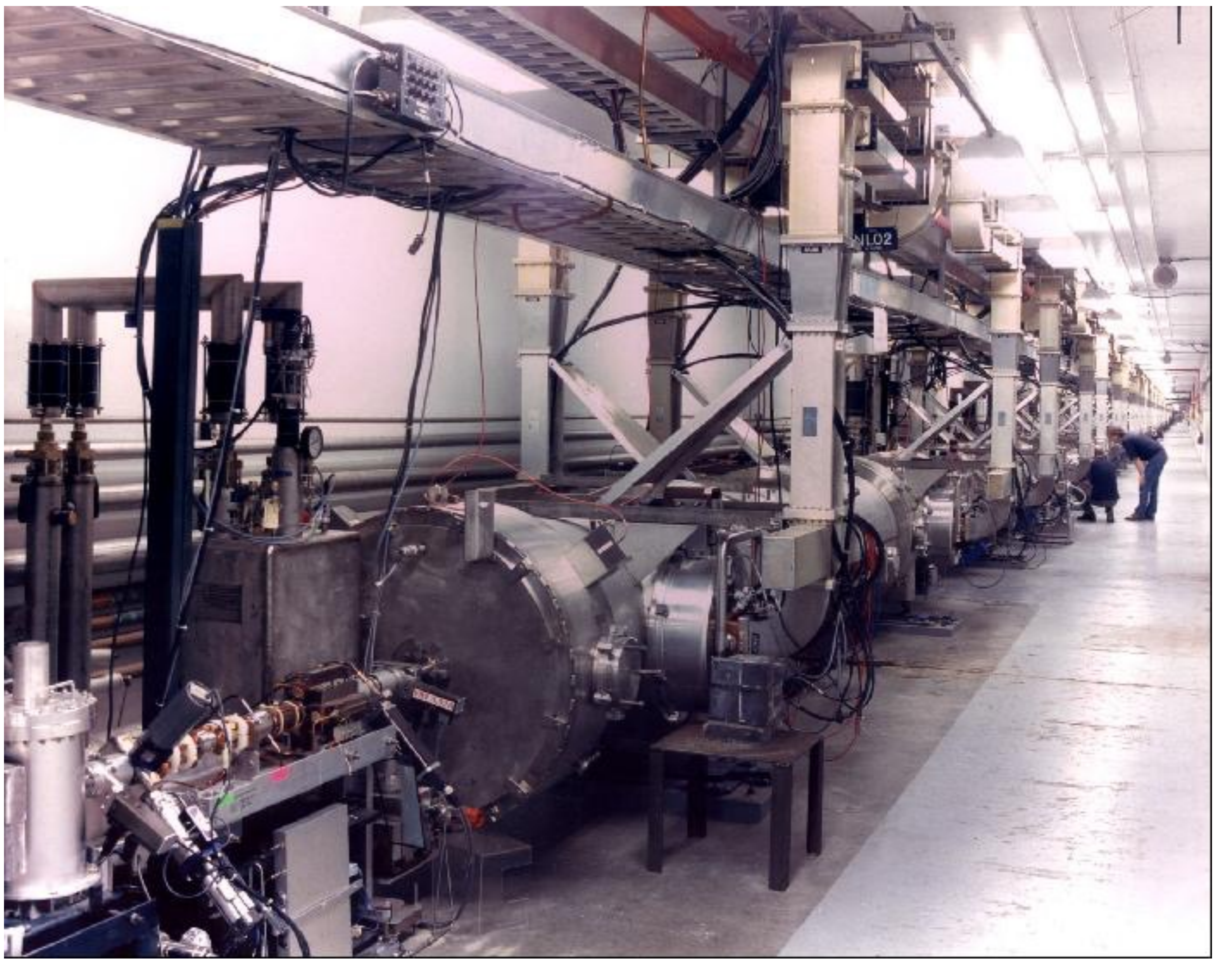
Up to 12 GeV beam energy

> 99.999% the speed of light

Electron's energy = rest mass of 12 protons…

5 times around 7/8 mile track in 30 microseconds

Accelerator requires 20 MW power

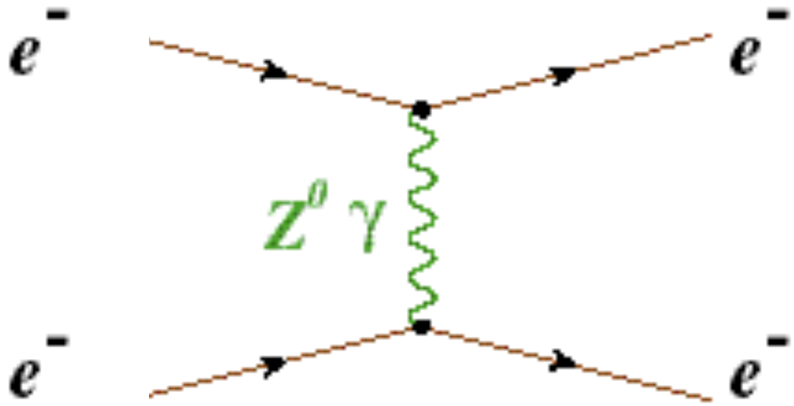


Bending magnets in arc

Linac tunnel

one million electrons every nanosecond

Weak charges



The strength with which the electron interacts via the Z^0 boson (weak interaction) is called the weak charge.

In the Standard Model, the weak charge of the electron is well predicted in terms of one of the fundamental parameters of the model, the electroweak mixing angle: $\sin^2\theta_W$

$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$

In the Standard Model, the weak charges of the electron and of the proton are predicted to be *the same*…

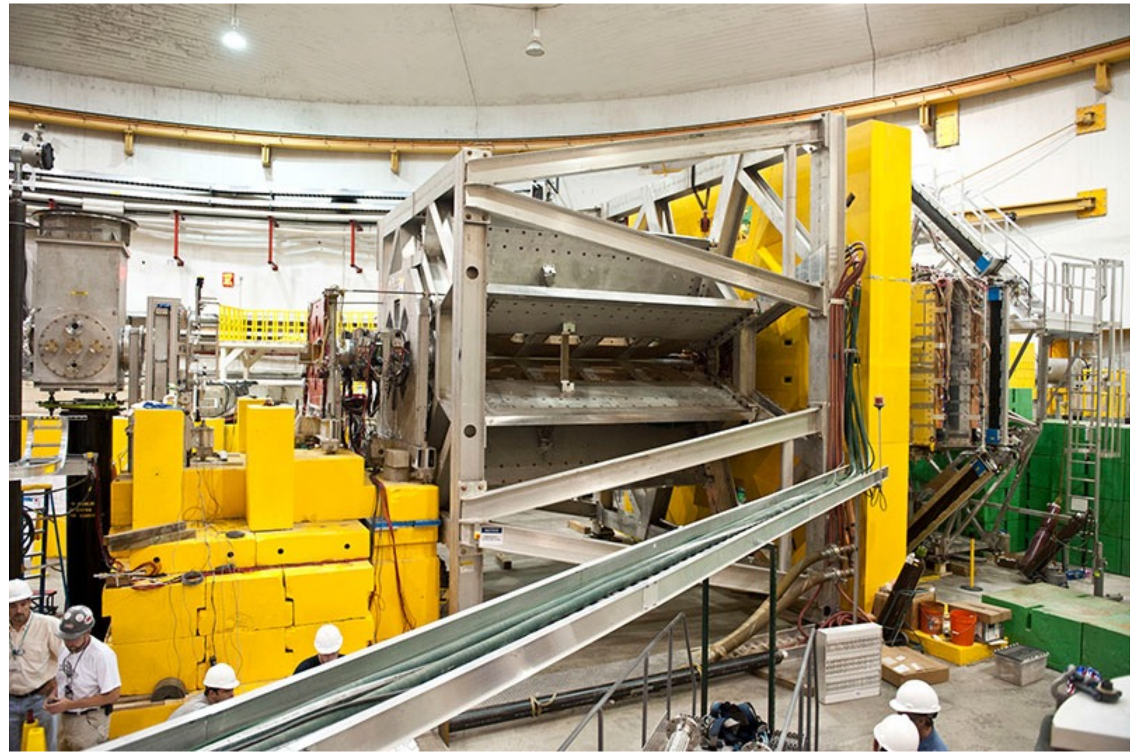
Previous Experiment: Qweak

- **At JLab, we measured the weak charge of the proton**

- Custom designed apparatus
- Data-taking: 2010 – 2012
  (~ 1 year total beam time)

- Jefferson Lab record
  beam current: 180 μA

- Final result:
  Nature 557, 207 (2018)



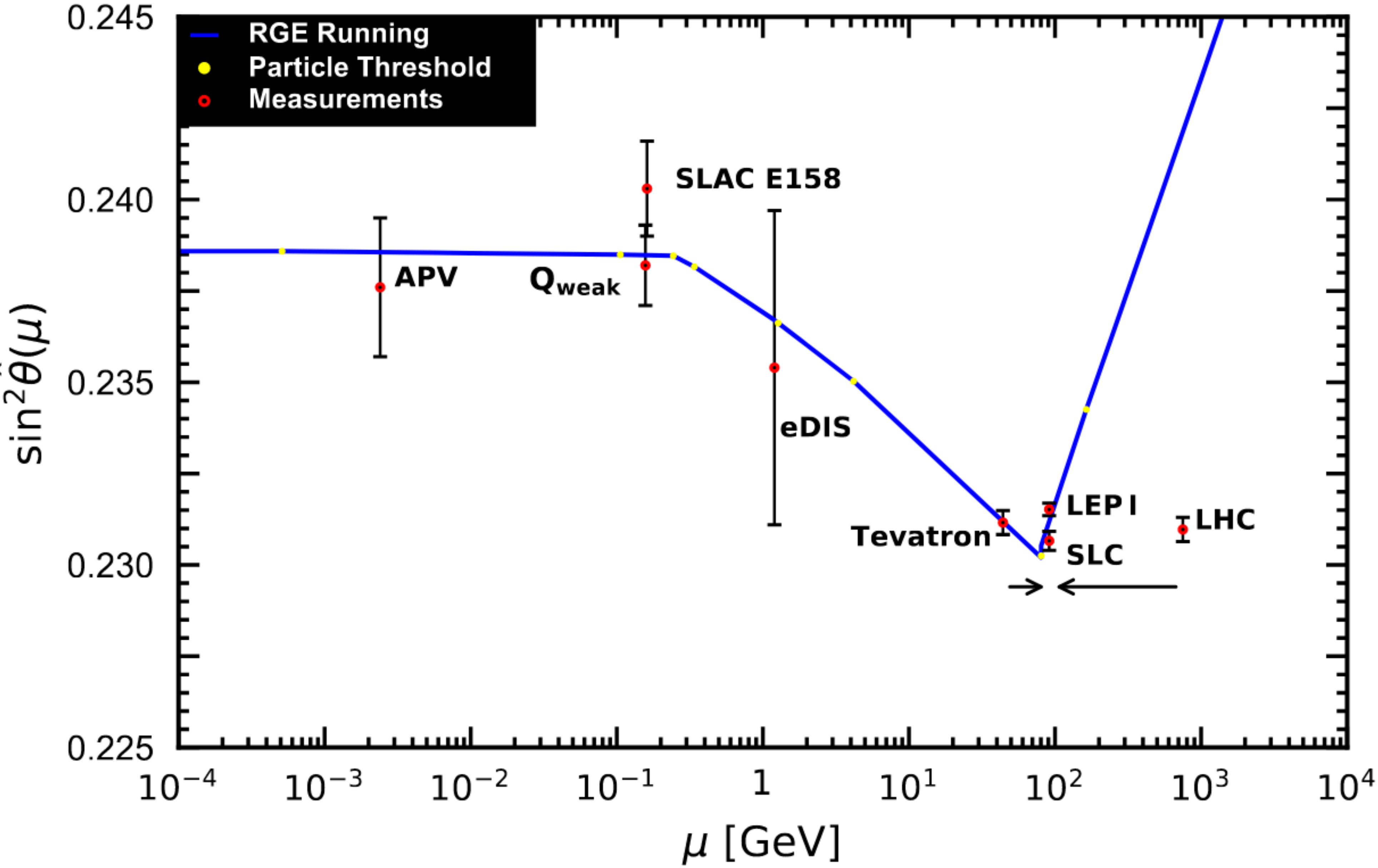
Standard Model:

$$Q_W^p = 0.0708 \pm 0.0003$$

Experiment:

$$Q_W^p = 0.0719 \pm 0.0045$$

Previous Measurements of $\sin^2\theta_W$



MOLLER goal

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

- Measure: $A_{PV} \approx 35$ ppb to 0.73 ppb precision
- Will give weak charge: $Q_W^e = 1 - 4\sin^2\theta_W$
  with 2.4% precision
- Will give $\sin^2\theta_W$ to 0.1% precision
- Will match precision of best previous measurements

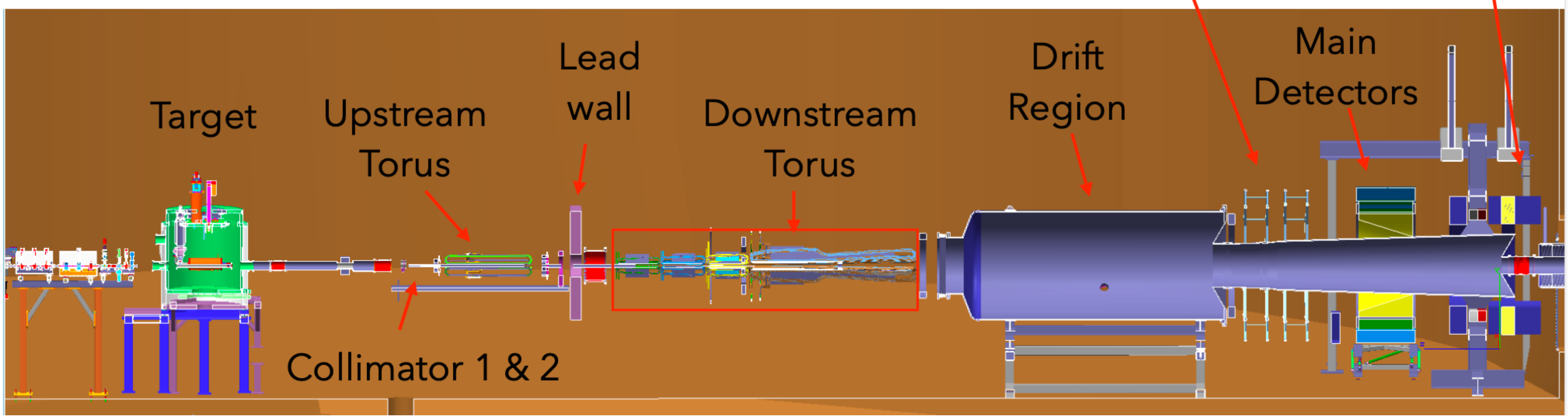
Requires:

11 GeV longitudinally-polarized electron beam

Detected flux of 135 GHz
8200 hrs data taking
3×10^{18} detected electrons

Custom Apparatus in Hall A at Jefferson Lab

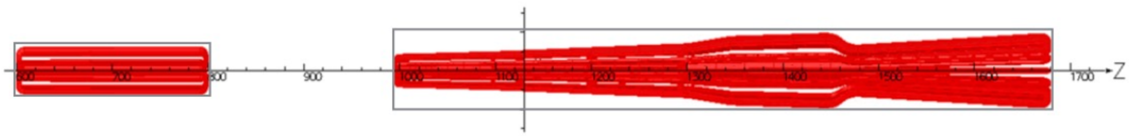
Experimental Overview



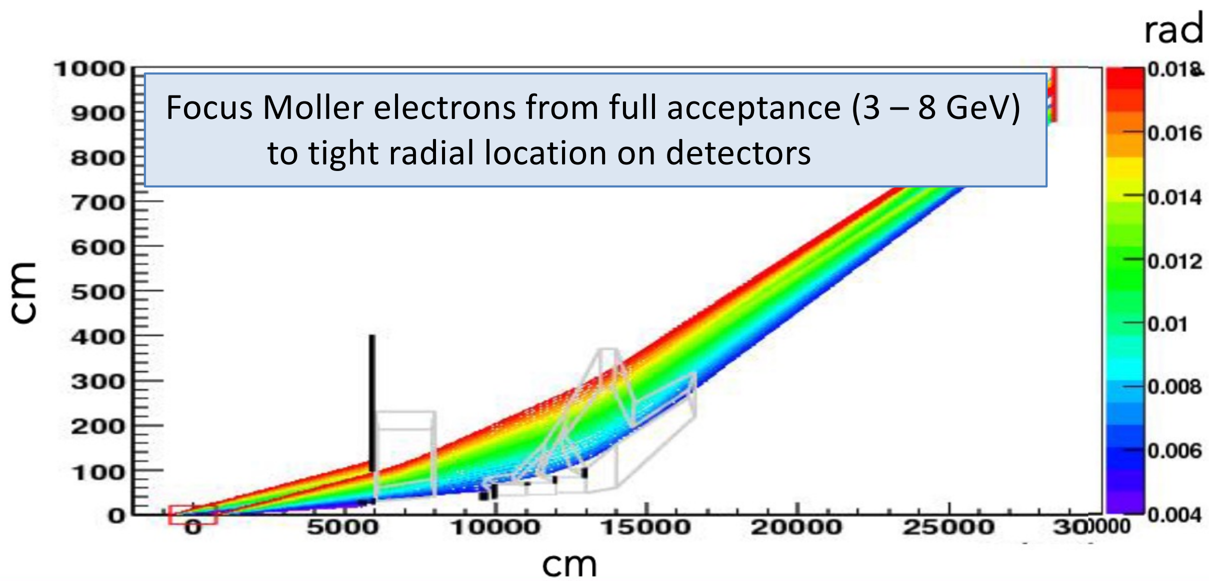
- Target: liquid hydrogen
- Measure those electrons that scatter at very small angles (0.25° to 2.4°)
- Torus magnets (donut-shaped magnetic field) to bend scattered electrons onto main detectors, separate electron-electron scattering from electron-proton scattering

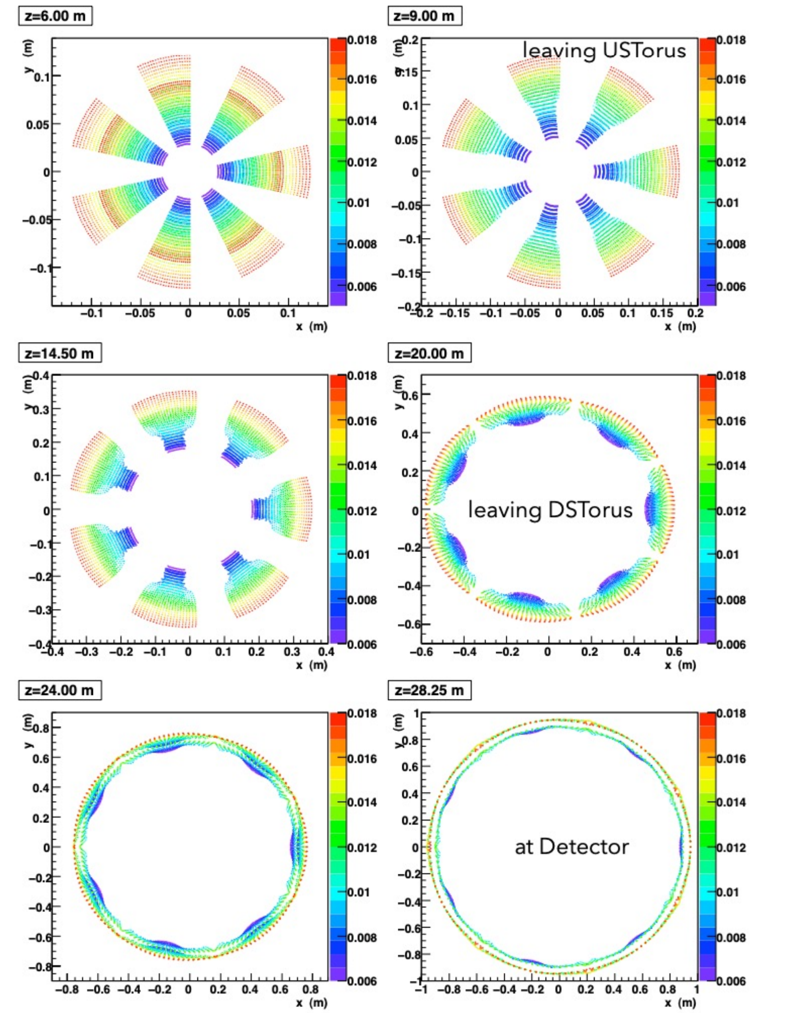
Magnets

long and skinny

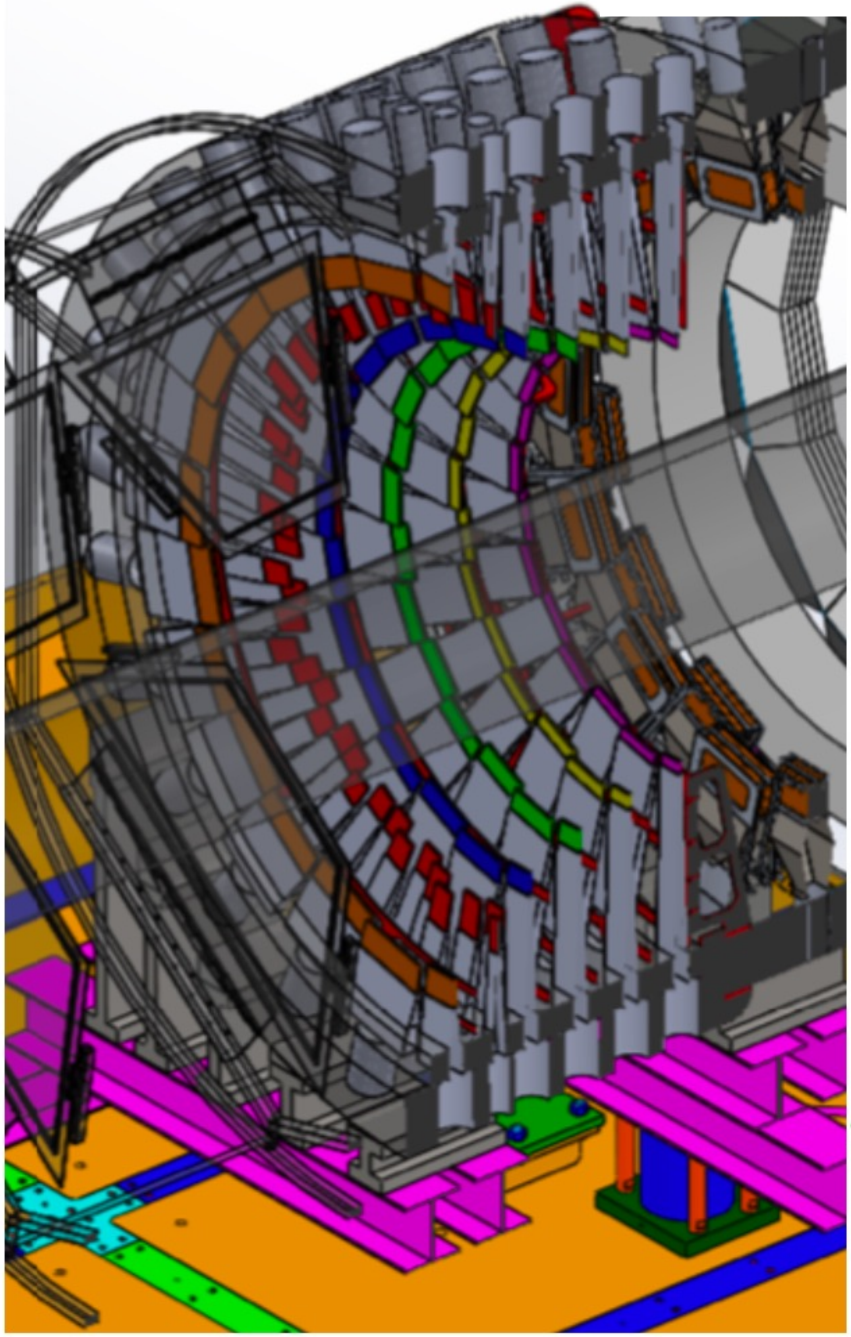


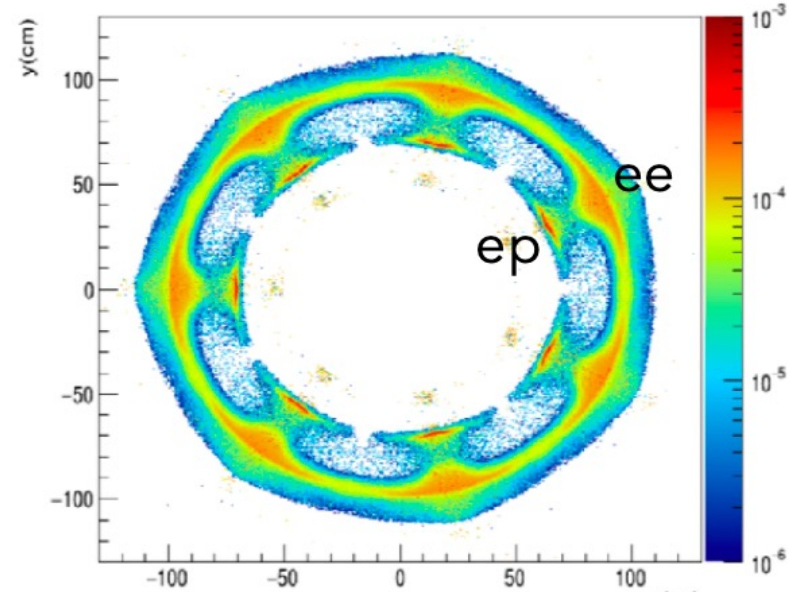
0.5 x 2m 0.9 x 6.5m

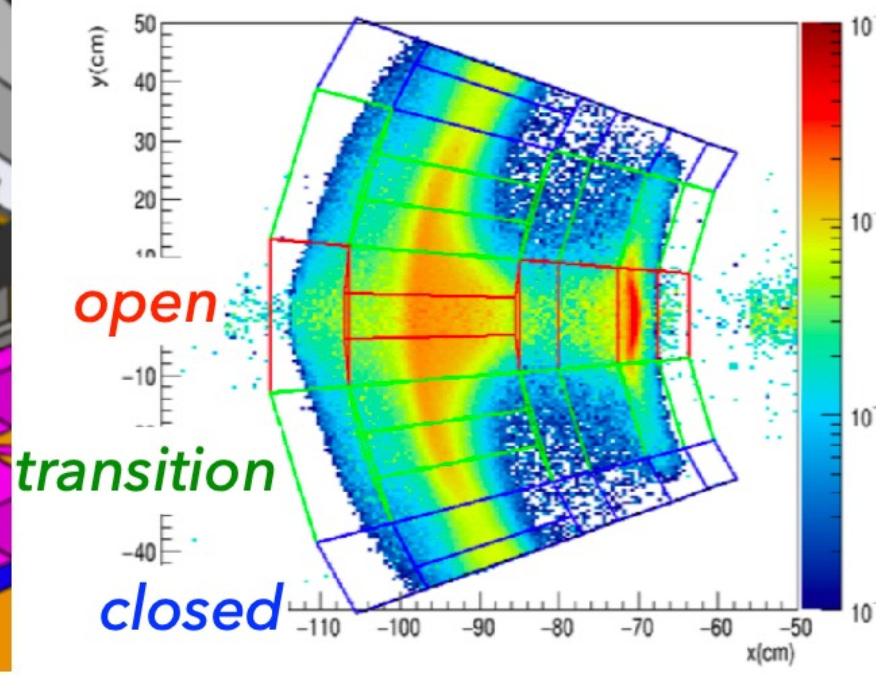




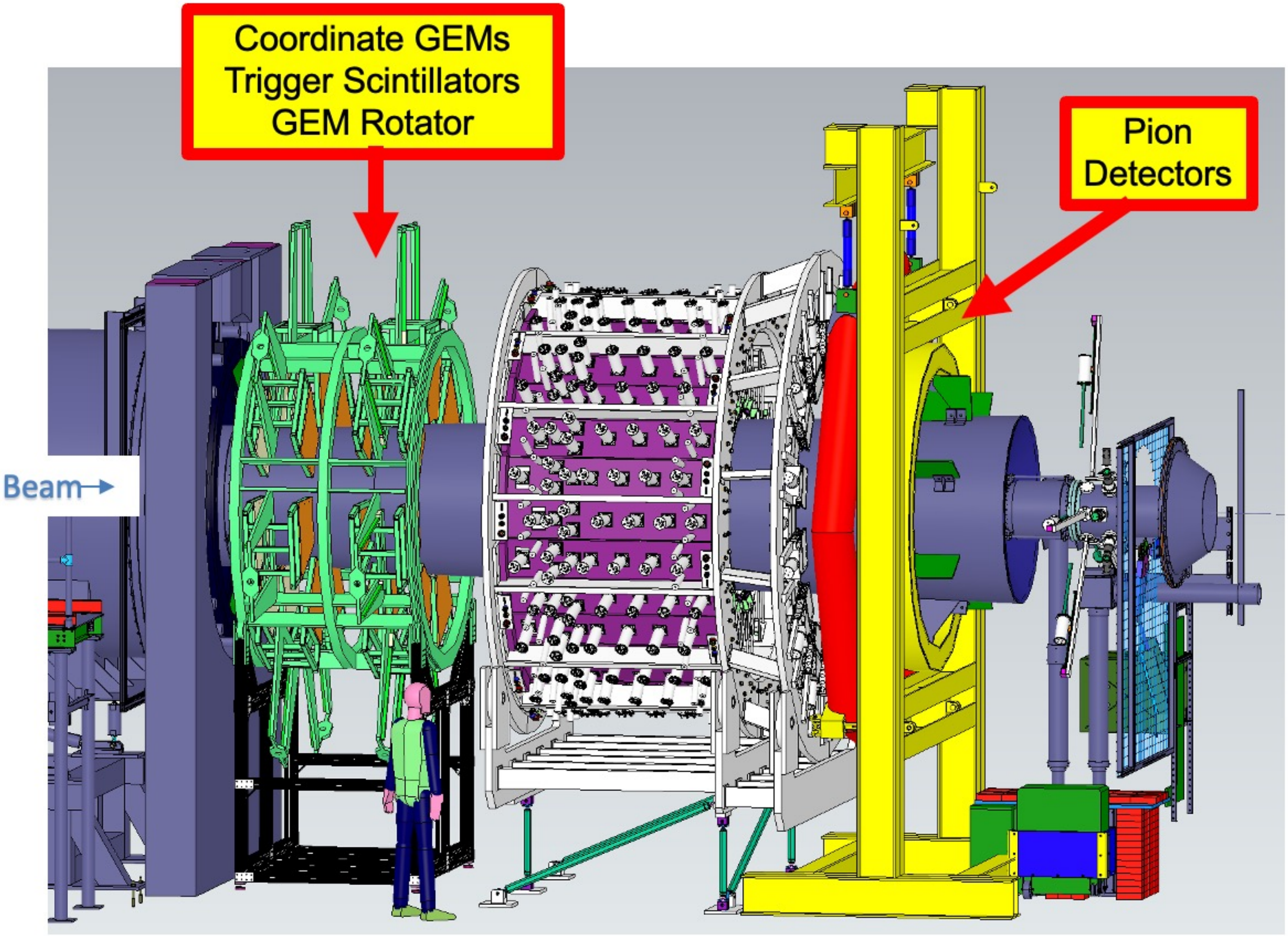
Main Detector







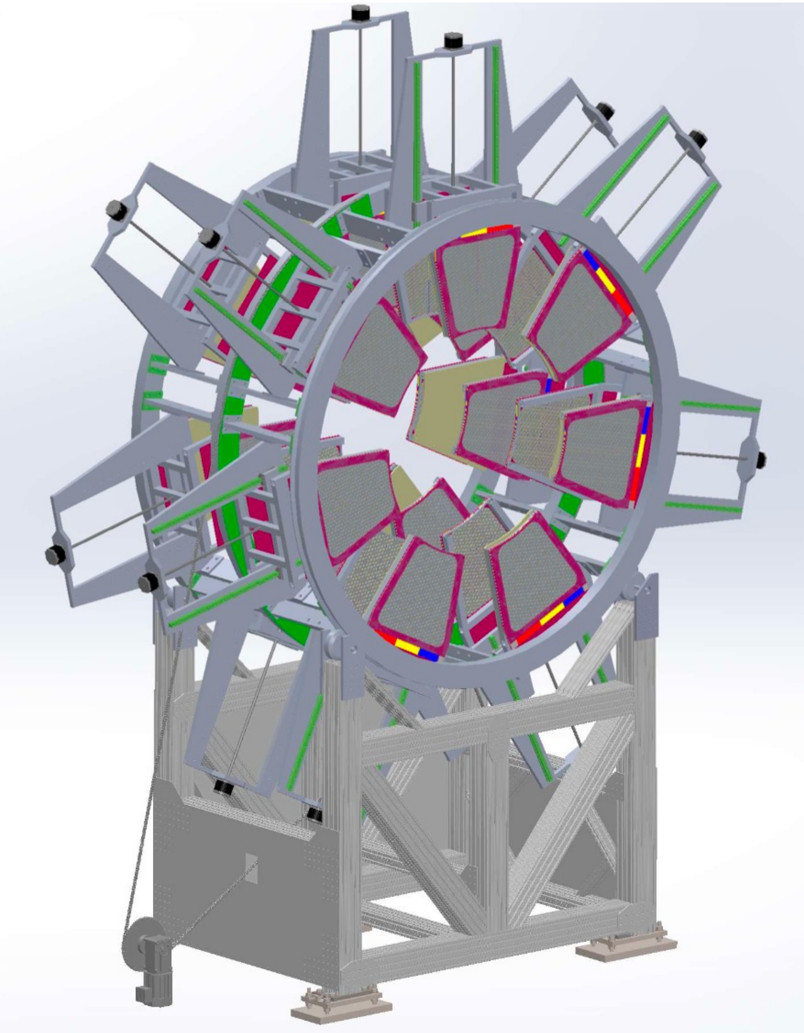
Additional Detectors



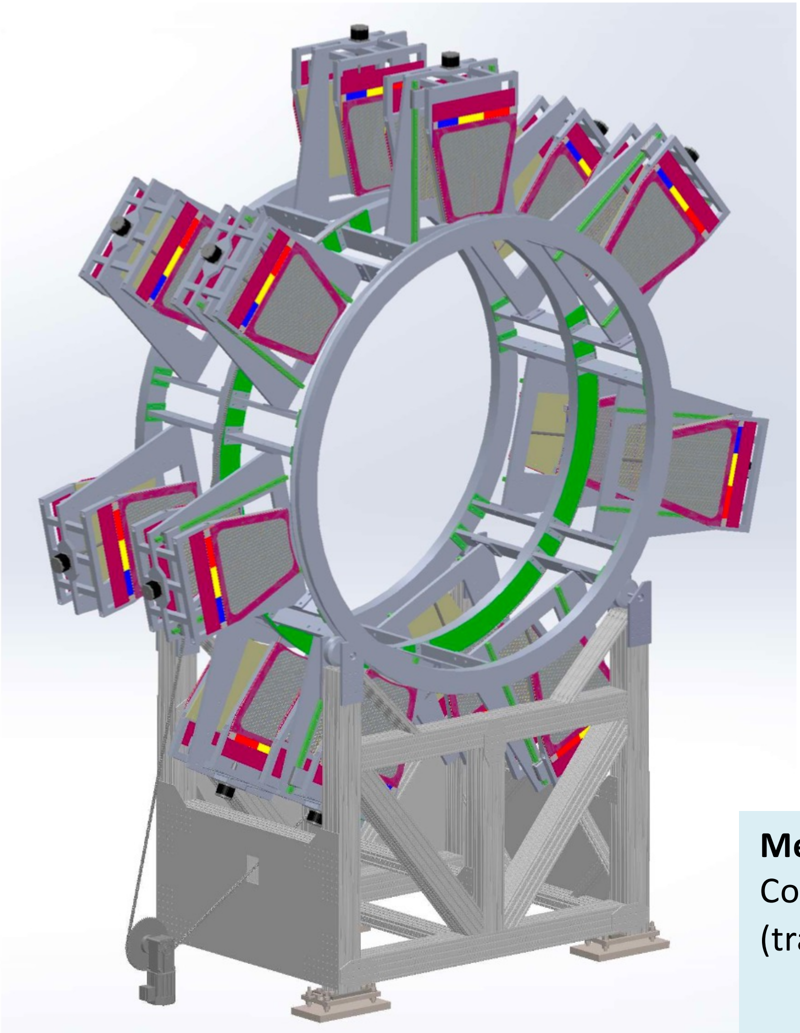
W&M is responsible for GEM Rotator & pion detectors

GEM Rotator

Measurement position



Parked position



Measurement position:
Counting mode
(tracking) data-taking

Parked position:
Integrating mode
(asymmetry) data-taking

Previous Student projects for MOLLER

- M. Tristan Hurst *"Pion Detection for the MOLLER Parity-Violating Electron Scattering Experiment"*
  honors thesis (May 2023)

- Gherson Gonzales Hernandez *"Cosmic Ray Testing of Pion Cherenkov Detectors"*
  senior thesis (Jan 2023)

- Lauren M. Carver *"Simulation and optimization of kinematics measurements for the MOLLER parity-violating electron-electron scattering experiment"*
  honors thesis (May 2021)

- Mary E. Robinson *"Machine Learning and Electron Track Reconstruction for the MOLLER experiment"*
  honors thesis (May 2019)

- Anne-Katherine Burns *"Pion Identification through Machine Learning for the MOLLER experiment at the Thomas Jefferson National Accelerator Facility"*
  honors thesis (May 2019)

- Jarod A. Worden *"MOLLER Beam Dump Simulations"*
  senior thesis (May 2019)

- Jacob McCormick *"GEANT4 Simulation of Pion Detectors for the MOLLER Experiment"*
  senior thesis (May 2017)

MOLLER Collaboration & Schedule

~160 authors, 37 institutions, 6 countries

Spokesperson: K. Kumar, UMass, Amherst

Executive Board Chair and Deputy Spokesperson: **M. Pitt**, Virginia Tech

Other Executive Board Members: D. Armstrong (William & Mary), J. Fast (JLab), C. Keppel (JLab), F. Maas (Mainz), J. Mammei (Manitoba), K. Paschke (UVa), P. Souder (Syracuse U.)

Major Equipment Funding:

U.S. Dept of Energy
U.S. National Science Foundation
Canada Foundation for Innovation/Research Manitoba
NSERC

Present Status: Engineering, Design, Prototyping, initial construction

More information: arXiv/1411.4088

Data-taking: 2026-2029

Summary

- We want to discover where the Standard Model starts to fail….
- Weak interaction violates parity – allows us to measure the strength of the weak interaction, *i.e.* the the weak charges of the electron and the proton.
- The weak charges are well-predicted by the Standard Model.
- Weak charge measured through tiny parity-violating asymmetry A_{PV}

Qweak: made precision measurement of A_{PV} in electron-proton scattering

- $\sin^2\theta_W$ to 0.46% – excellent agreement with Standard Model prediction

MOLLER: will be a precision measurement of A_{PV} in electron-electron scattering

- $\sin^2\theta_W$ to 0.1% $\rightarrow$ ultra-precision Standard Model test