Acknowledgements:
Numerous physics colleagues who have educated me over the years

Parity Violation at Jefferson Lab and Beyond

Searches for New Neutral Current Interactions
Lecture III

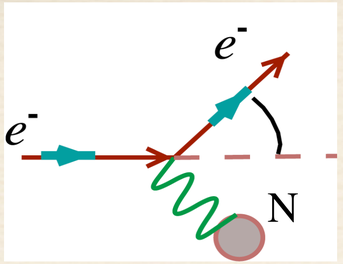
Krishna Kumar
University of Massachusetts, Amherst

CNUGS26, Jefferson Lab
June 5, 2026

Lecture 3 Outline

- Historical Introduction to Parity-Violating Electron Scattering
- Weak Neutral Current Interactions and the Weak Mixing Angle
- First Low Energy Precision Measurement: SLAC E158
- Qweak and PVDIS
- Future: MOLLER, P2, SoLID
- Summary

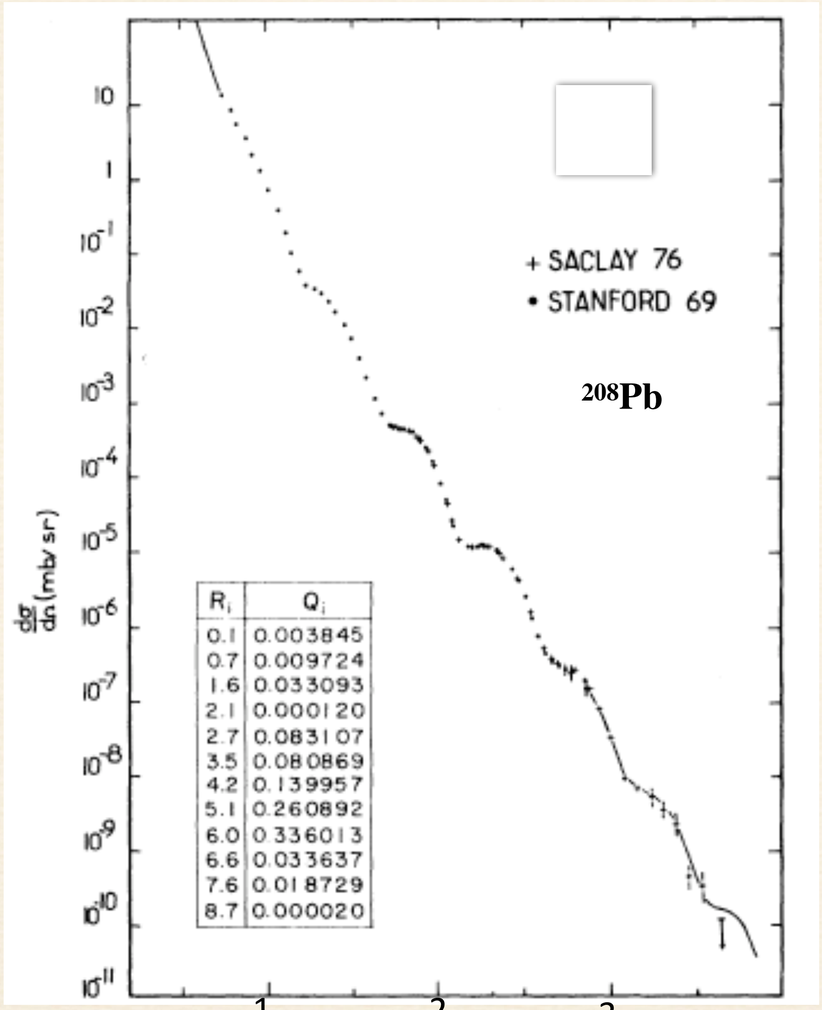
Historical Context

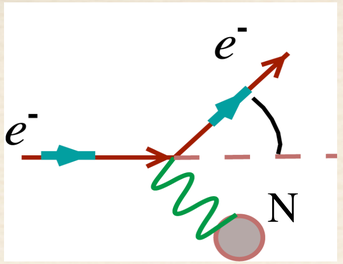


Electron interactions are well-understood

Fixed Target e- Scattering

Special Relativity, Dirac Equation and Quantum Mechanics



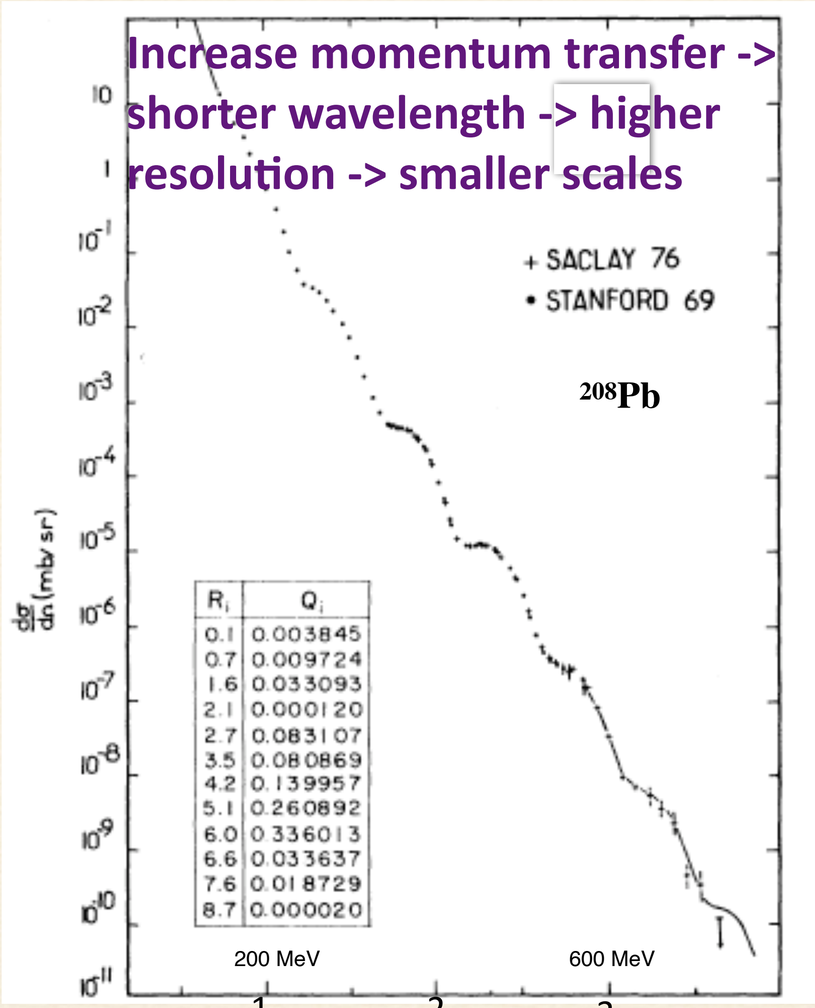


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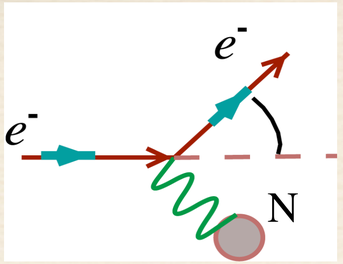
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Increase momentum transfer -> shorter wavelength -> higher resolution -> smaller scales



R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020



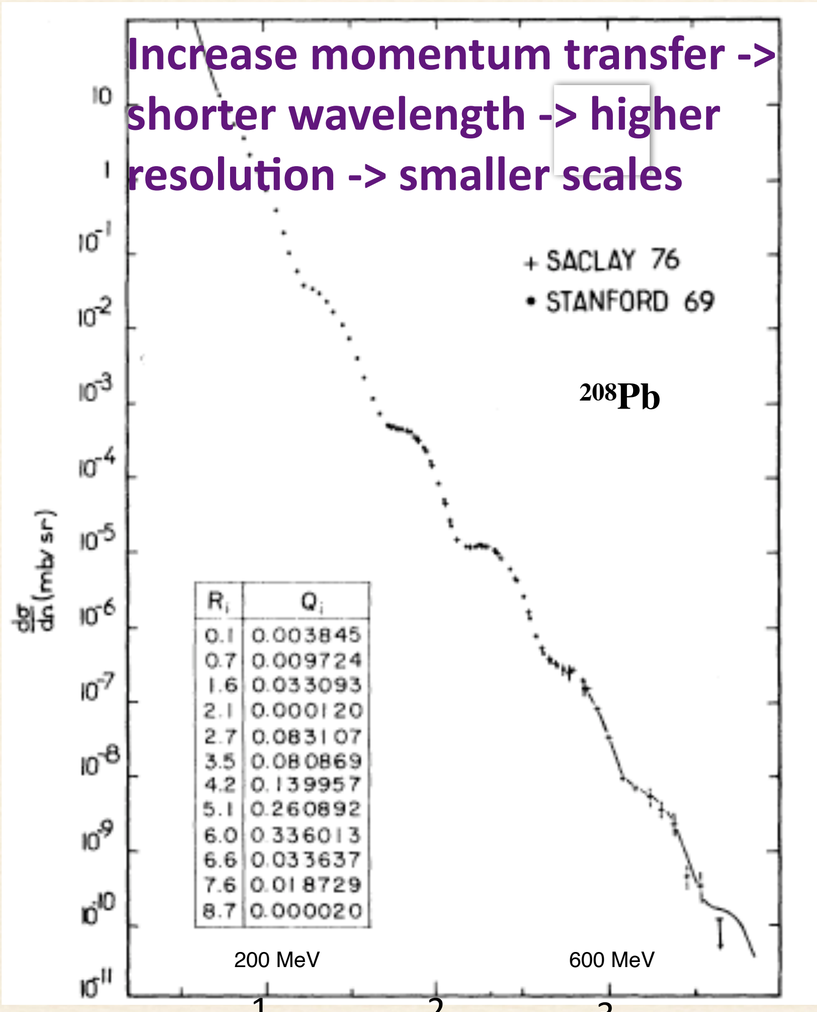
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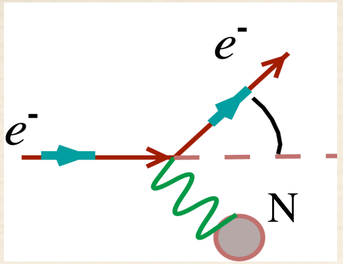
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Modified Differential Cross Section

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(q)|^2$$





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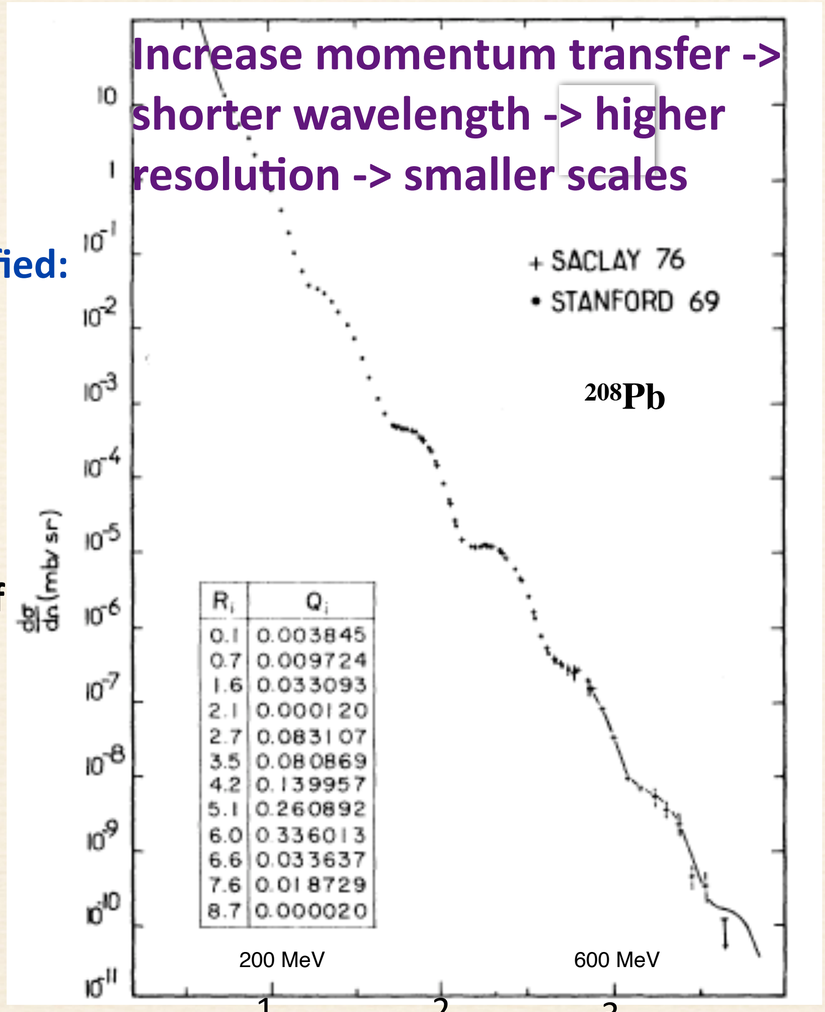
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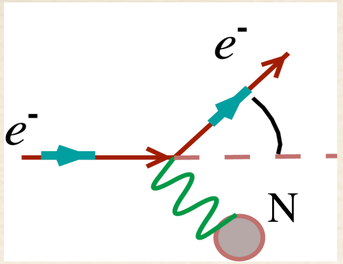
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The point-like scattering probability modified: Introduce a "form factor"

$$F(q) = \int e^{iqr}\rho(r)d^3r$$

Form factor is the Fourier transform of charge distribution





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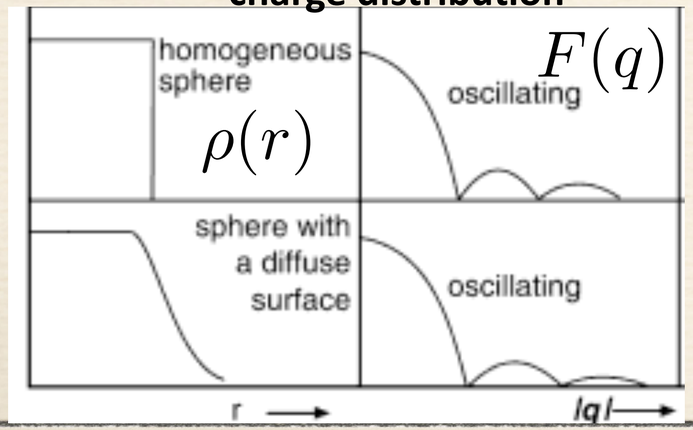
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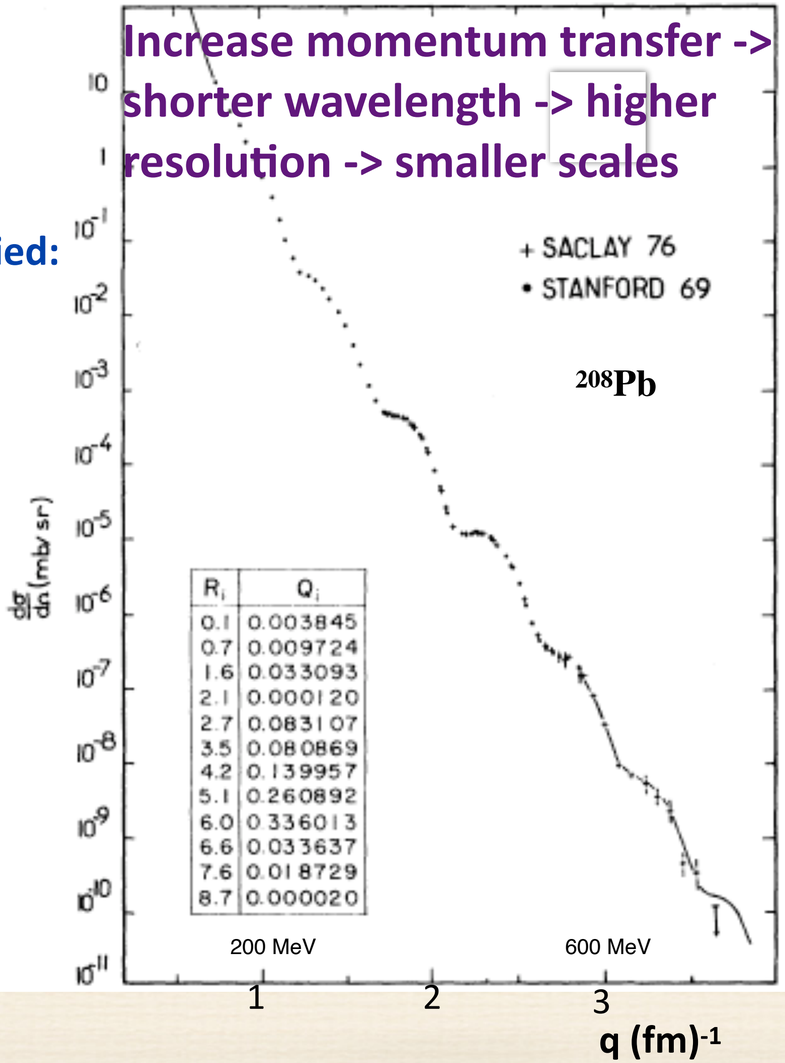
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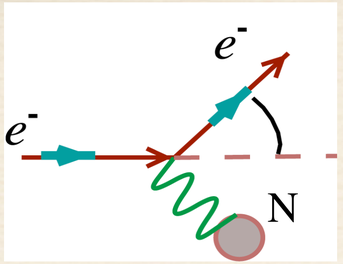
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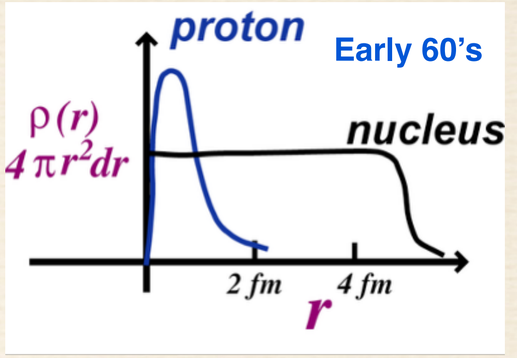


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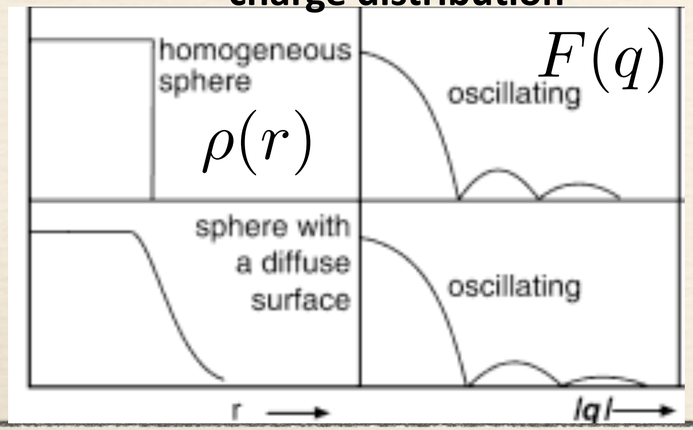
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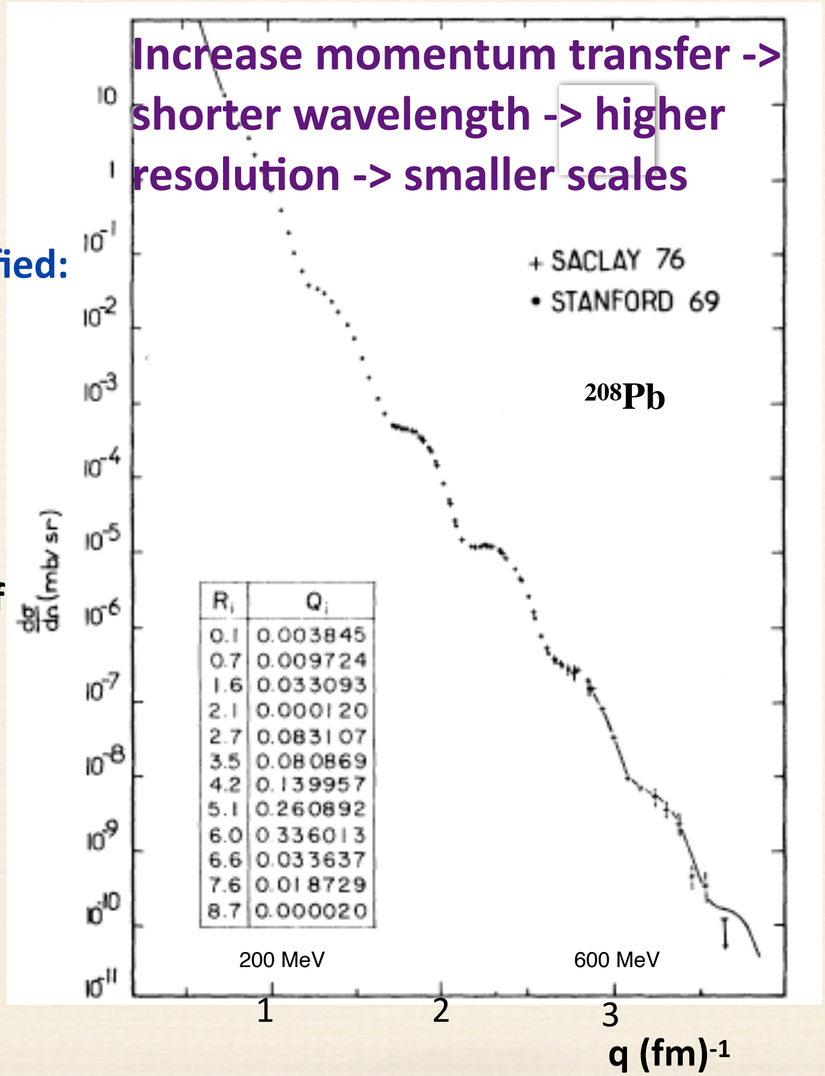
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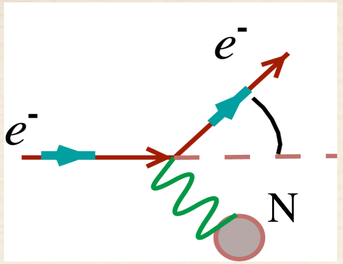
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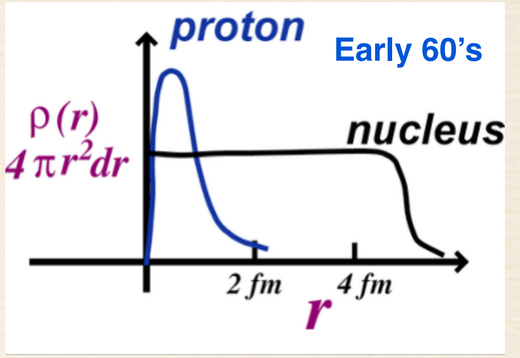


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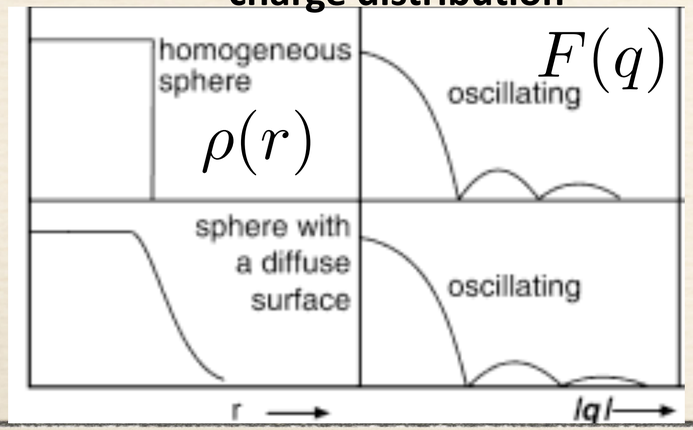
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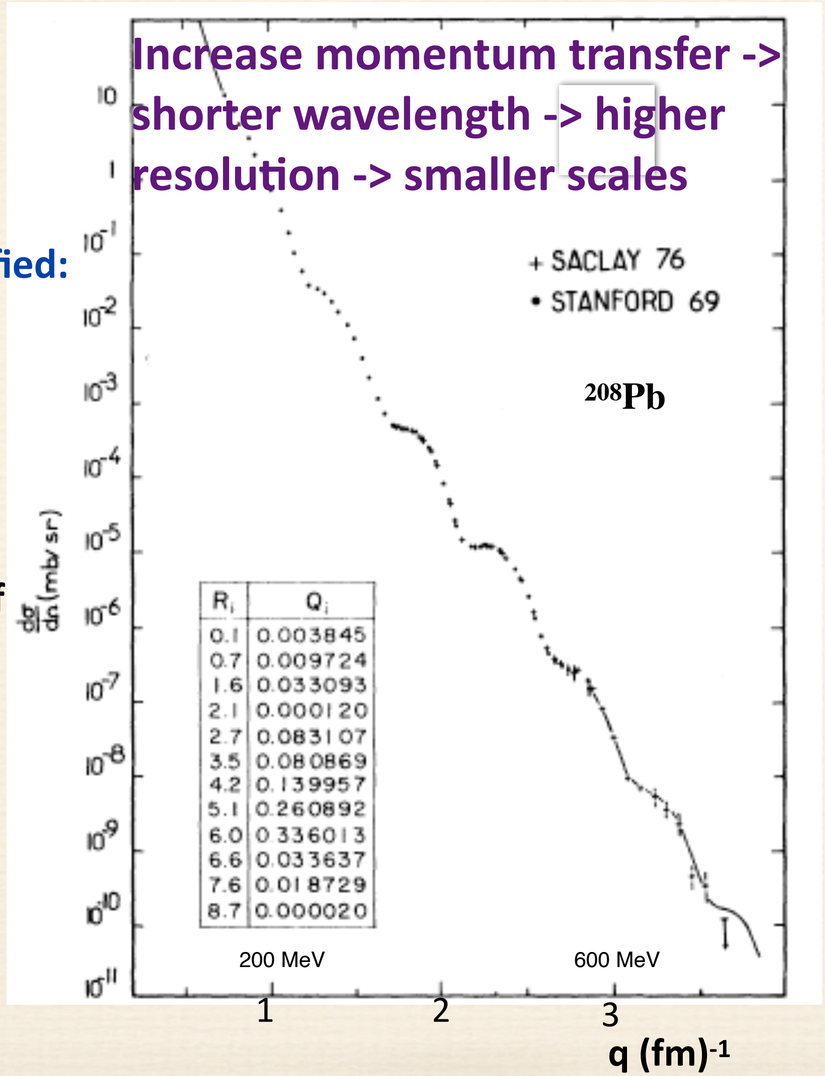
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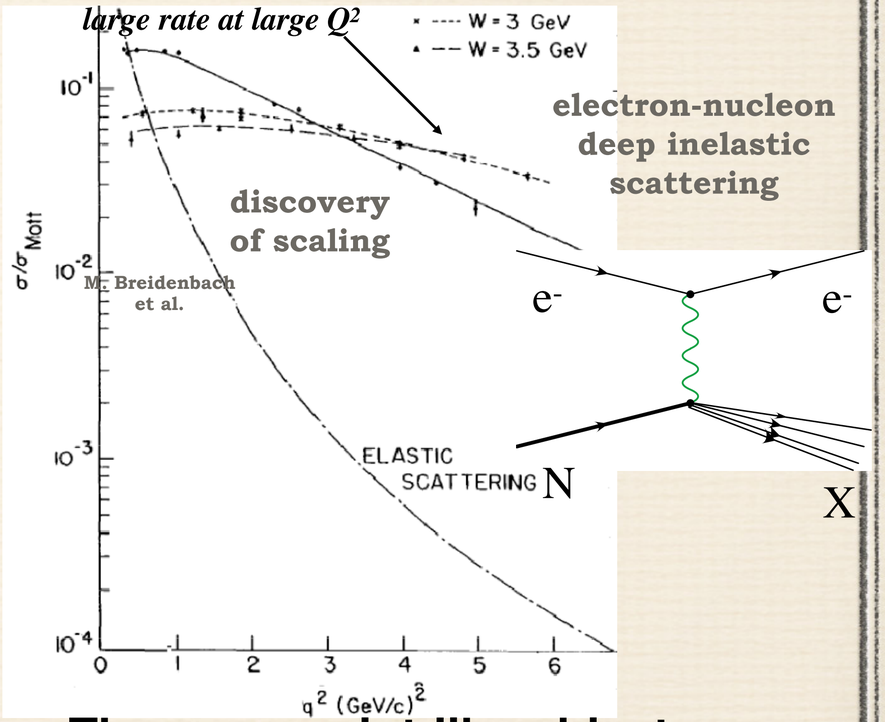
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Mid-1960's, SLAC was able to reach multi-GeV energies

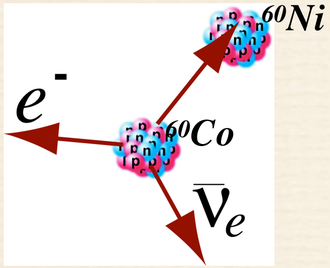


There are point-like objects inside the proton —> Quarks!

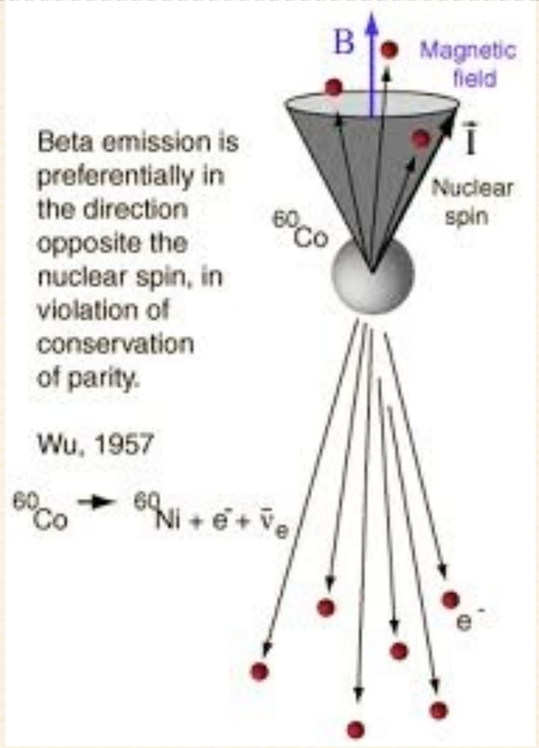
Reminder

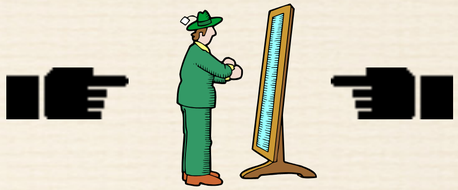
parity transformation (reflection)

$$x, y, z \rightarrow -x, -y, -z$$



Weak decay of ^{60}Co Nucleus





$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{s} \rightarrow \vec{s}$$

matter particles have spin = 1/2

$$h = \frac{\vec{s} \bullet \vec{p}}{|\vec{s}||\vec{p}|} = \pm 1$$

handedness or
helicity/chirality

Feynman and Gell-Mann proposed the the "V-A" form of the weak interaction

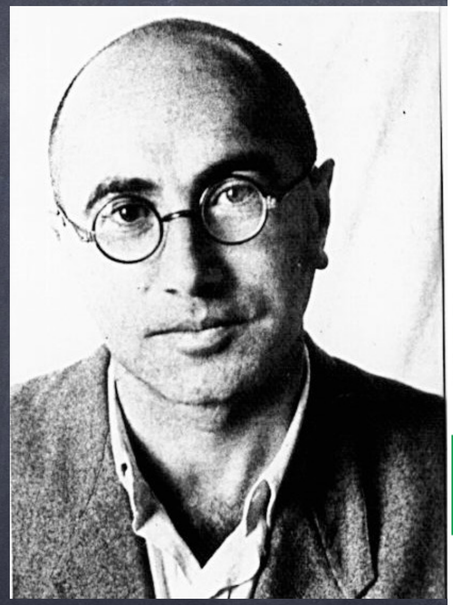
Vector and and Axial-Vector components to the "current" that describes the interaction

Mirror reflection flips sign of helicity

Left-handed ⟺ *right-handed*

Only left-handed particles can mediate W bosons
(right-handed anti-particles)

A Classic Paper



LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964–966 (March, 1959)

Brilliant Speculation

WE assume that besides the weak interaction that causes beta decay,

$$g\,(\bar{P}ON)\,(\bar{e}^{-}O\nu) + \text{Herm. conj.}, \qquad (1)$$

there exists an interaction

$$g\,(\bar{P}OP)\,(\bar{e}^{-}Oe^{-}) \qquad (2)$$

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

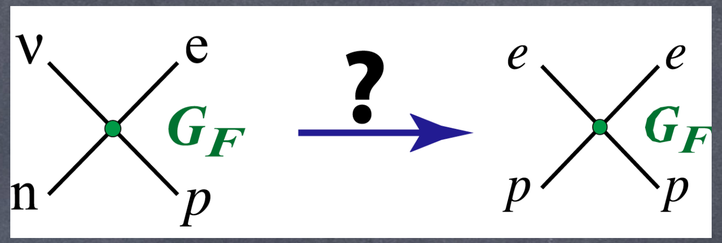
In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

Is there a neutral analog of the "charged" weak force?

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Neutron β Decay

Electron-proton Weak Scattering



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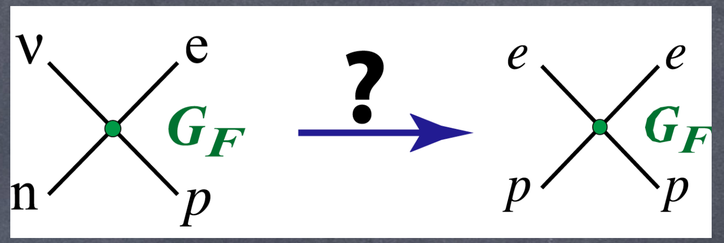
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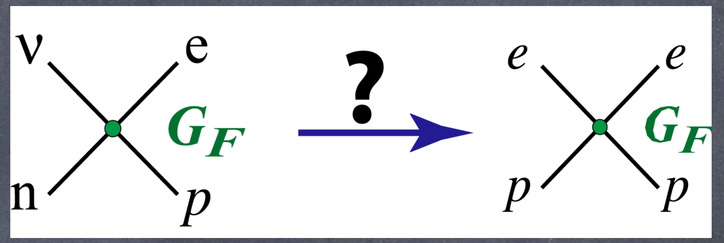
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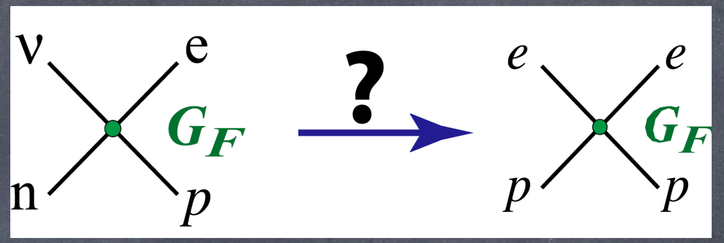
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$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = -A_{LR}$$

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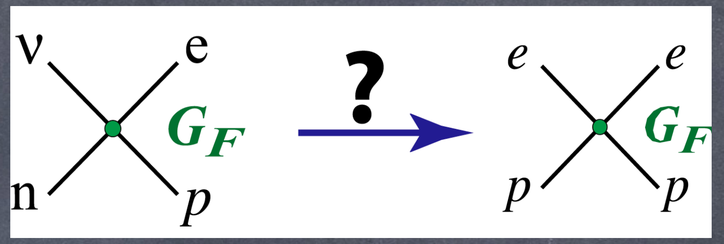
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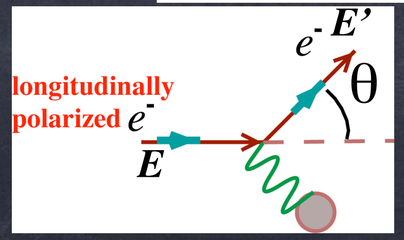


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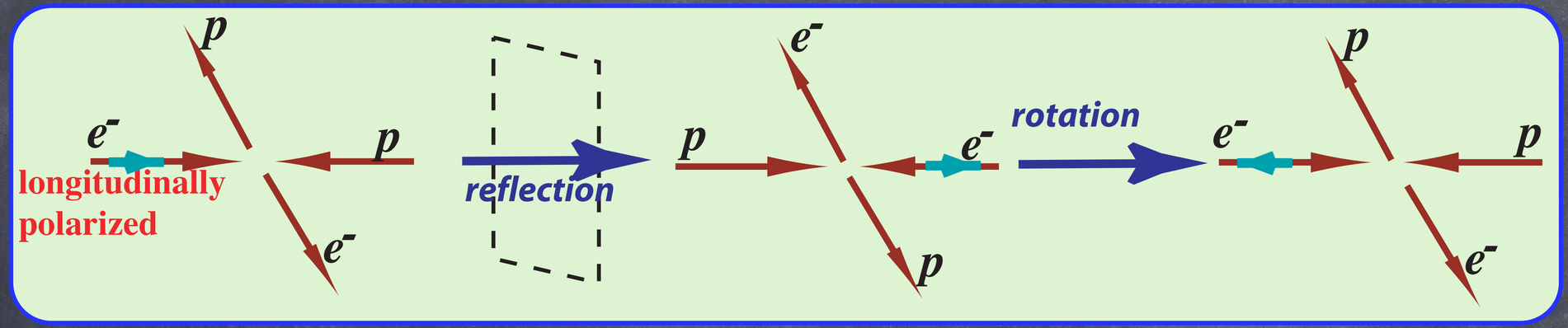


4-momentum transfer

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

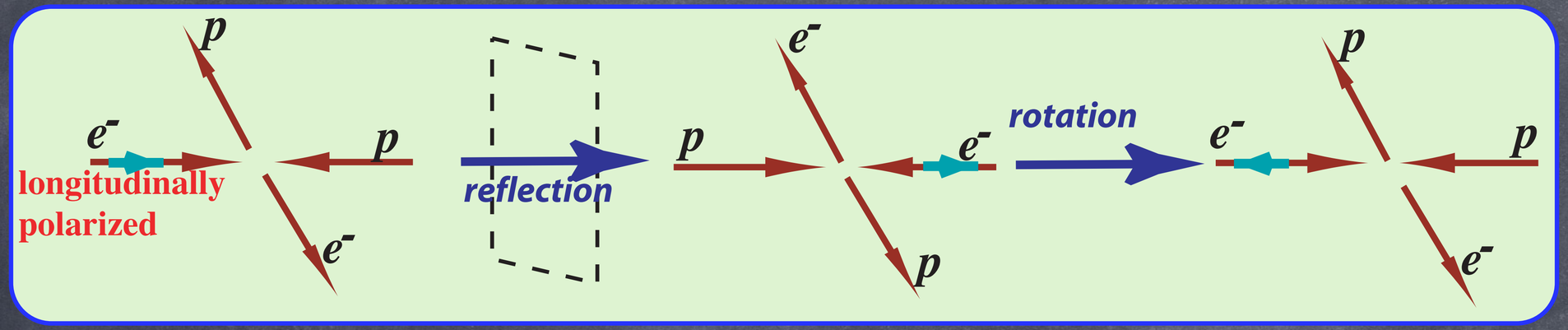
Parity-Violating Observable

How to measure parity violation in electron scattering



Parity-Violating Observable

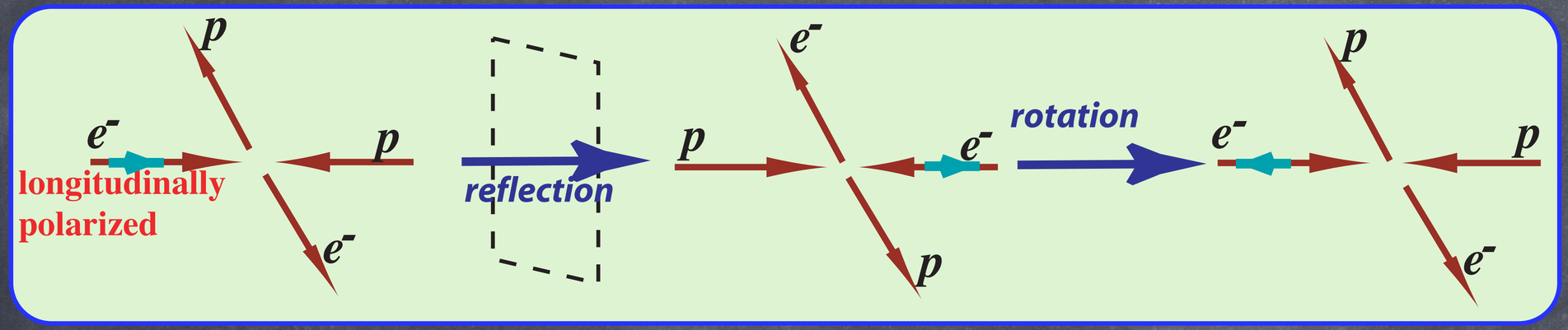
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- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

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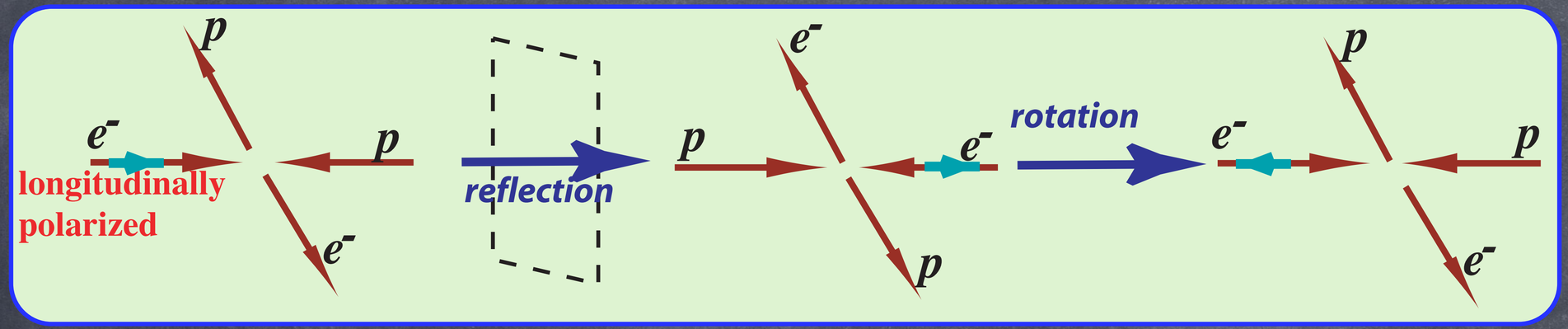


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The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity nonconservation effects can be of the order of 0.1 to 0.01 percent.

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$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$A_{PV} \sim 10^{-4} \cdot Q^{2}(\mathrm{GeV}^2)$$

1960's

Electroweak Unification

Accept the existence of u & d quarks, electrons, and electron-neutrinos

$SU(2)_L \times U(1)_Y$

2 couplings

4 conserved currents

local gauge invariance yields 4 bosons: W^+, W^-, W^0, B^0

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two weak charged currents	electromagnetic current	weak neutral current
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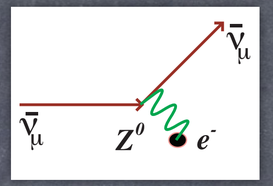
Mass to weak vector bosons and fermions, one Higgs boson, one free parameter: weak mixing angle θ_W

Remaining Piece

1970's



First weak neutral current event:
Gargamelle bubble chamber

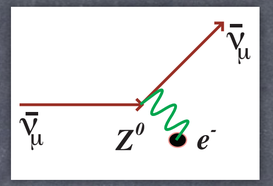


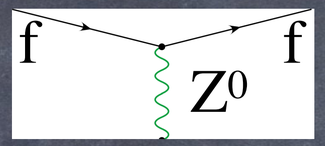
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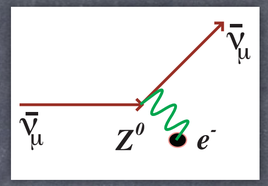
$$\frac{g}{\cos\theta_W} Z_\mu \bar{f} \gamma^\mu (T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5) f, \quad T_{3f} = \pm 1/2$$

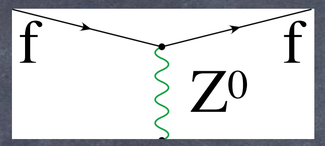
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Do lepton-quark neutral current interactions exhibit parity violation?

$$\begin{pmatrix}\nu \\ e\end{pmatrix}_l \quad (e)_r$$

or

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Weinberg model

Parity is violated

$$A_{PV} \sim 10^{-4}$$

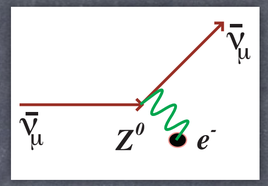
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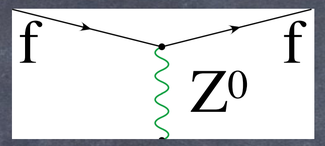
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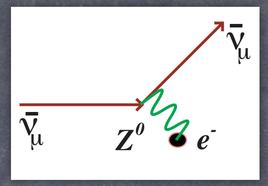
First table-top atomic parity violation searches: negative!

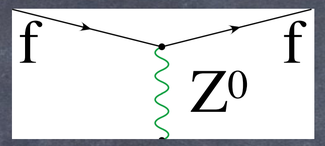
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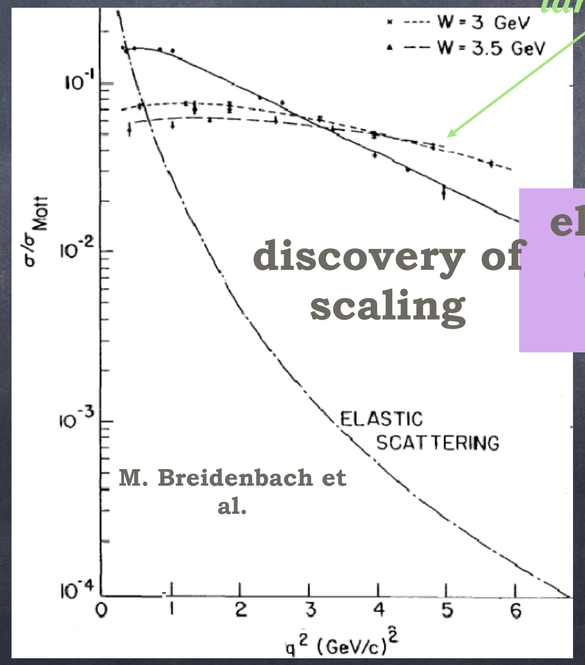
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large rate at large Q^2



electron-nucleon deep inelastic scattering

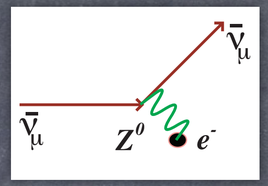
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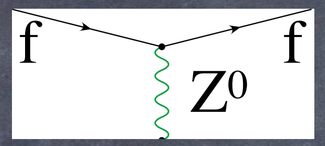
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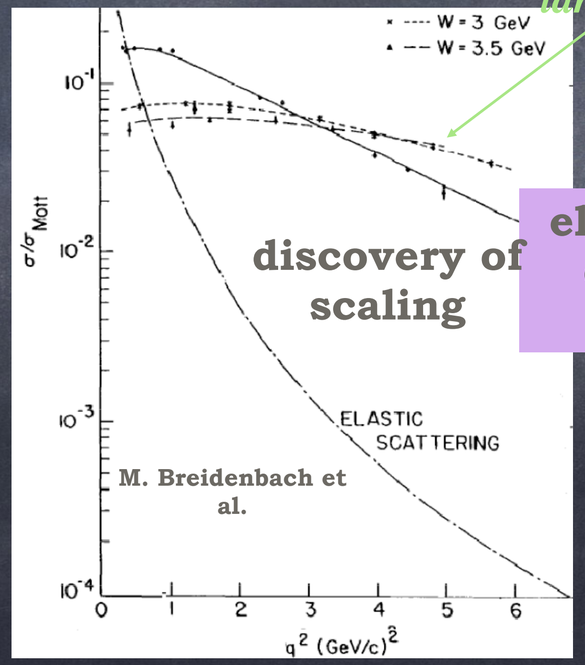
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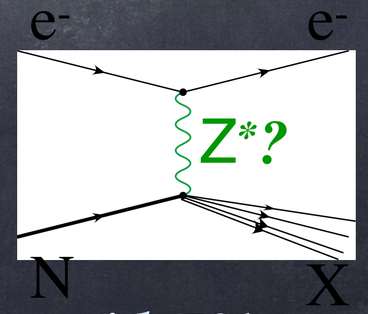
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pressing problem in mid-70's

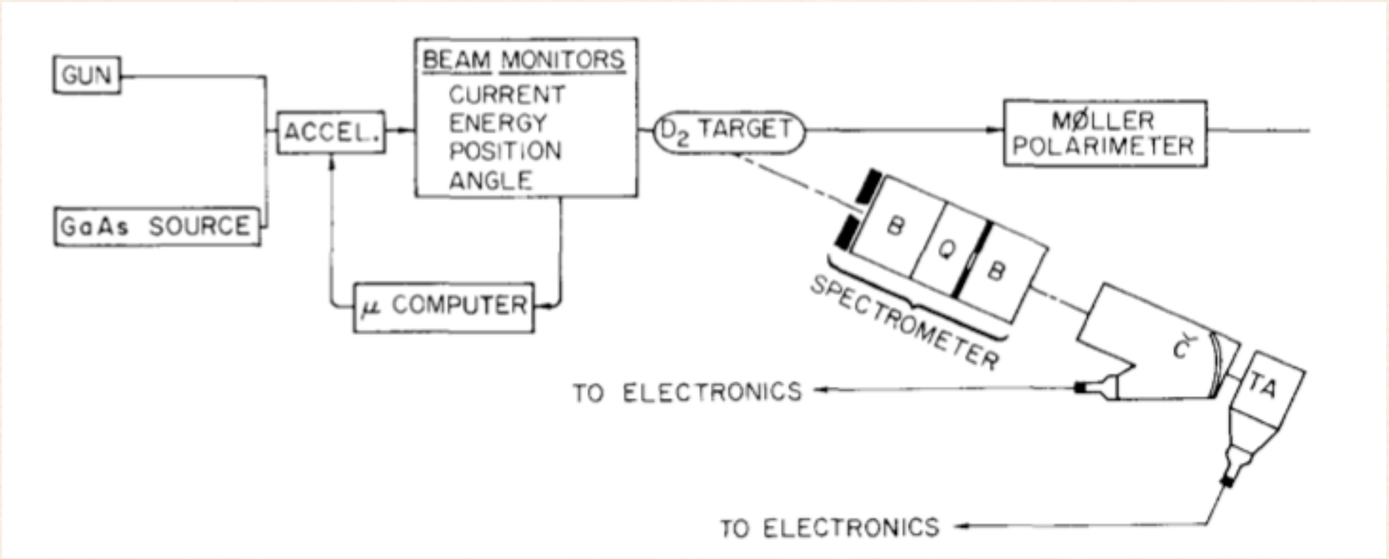
Seminal experiment launched the subfield of PV electron scattering

1978

SLAC E122

C.Y. Prescott, *et al*.





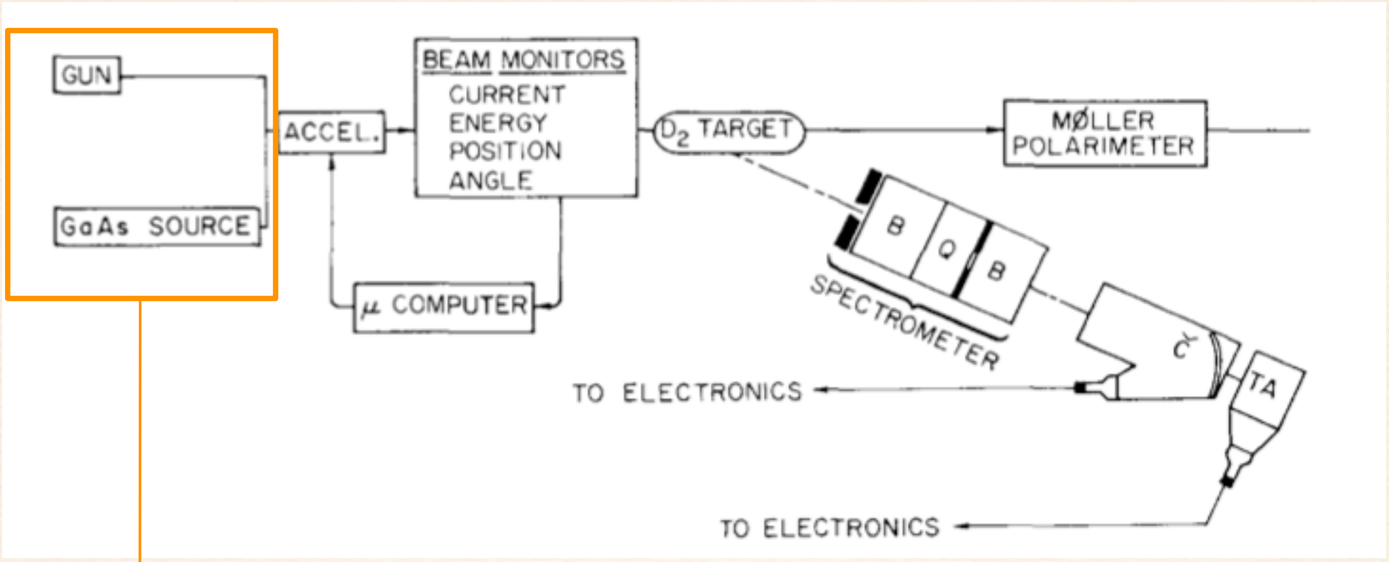
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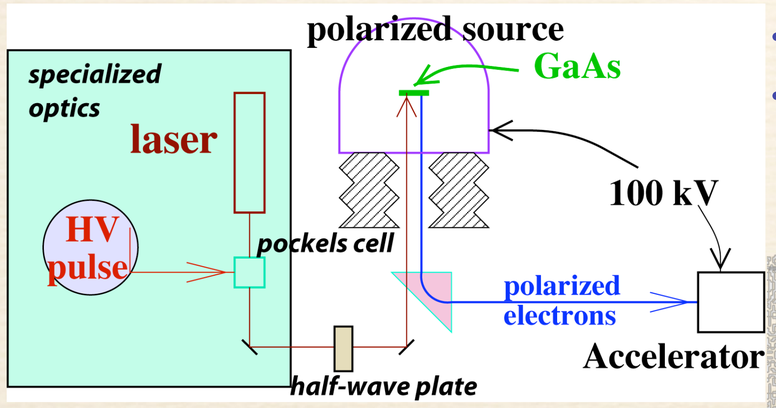
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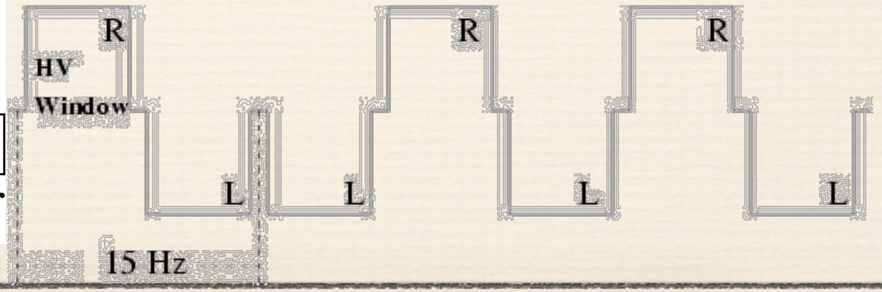






✧ **Beam helicity sequence is chosen pseudo-randomly**

- Helicity state, followed by its complement
- Data analyzed as "pulse-pairs"



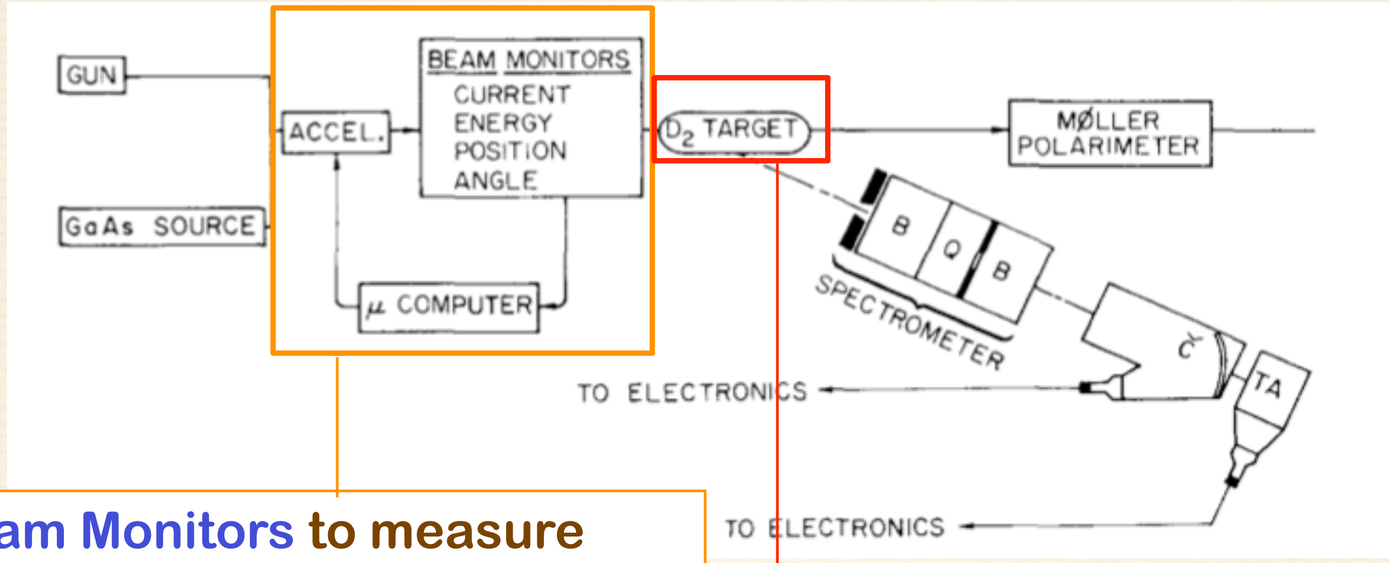
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- **Beam Monitors to measure helicity-correlated changes in beam parameters**

- **High-power cryotarget 30 cm long for high luminosity**

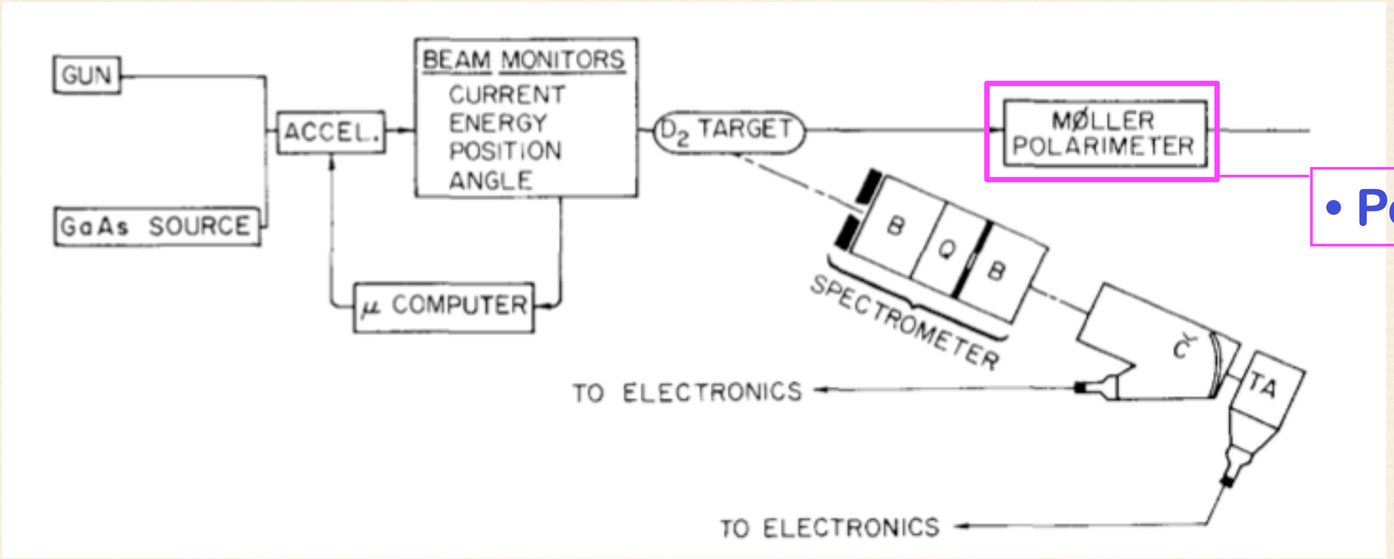
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- **Polarimetry**

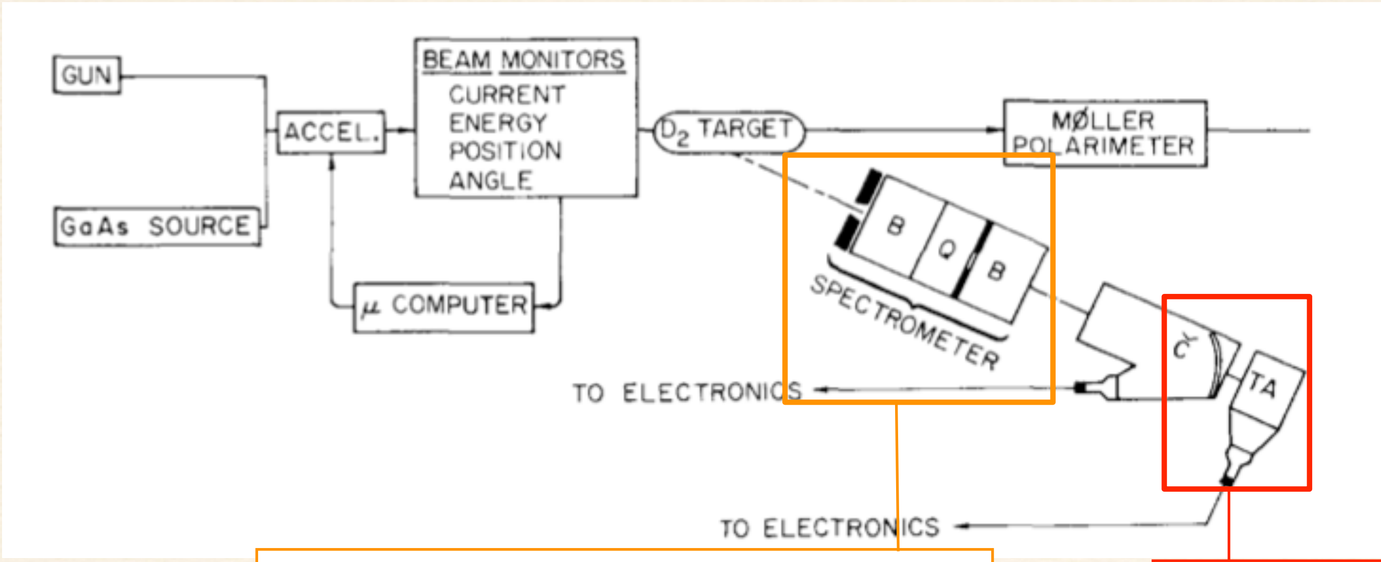
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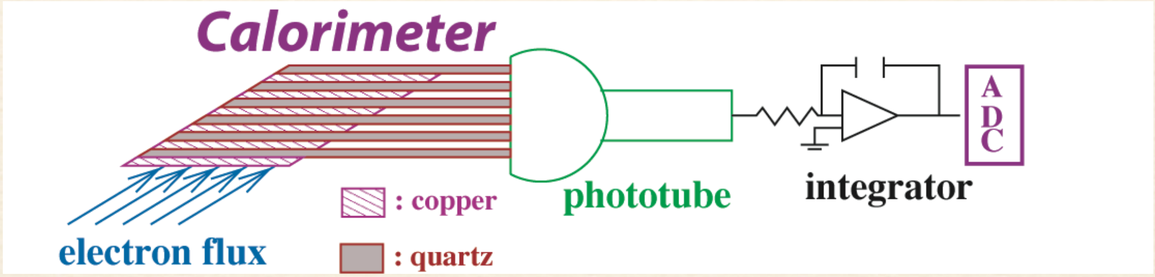
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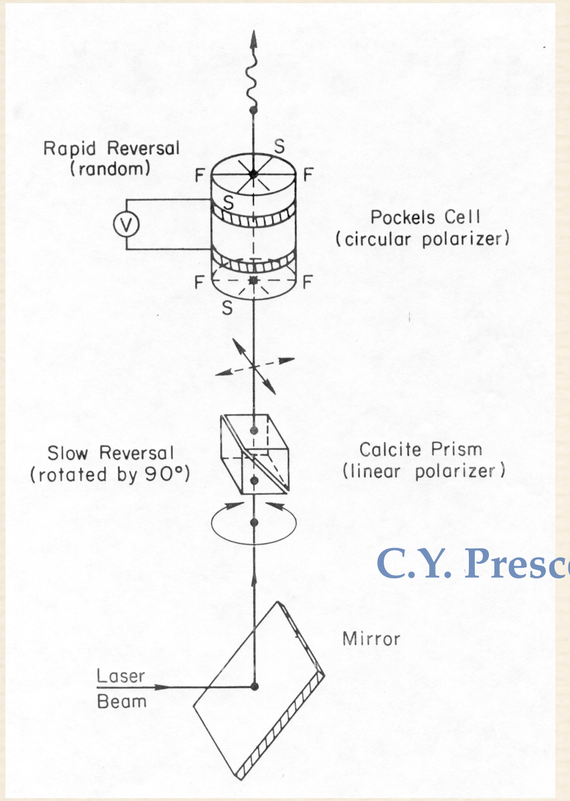
- **Magnetic spectrometer directs flux to background-free region**

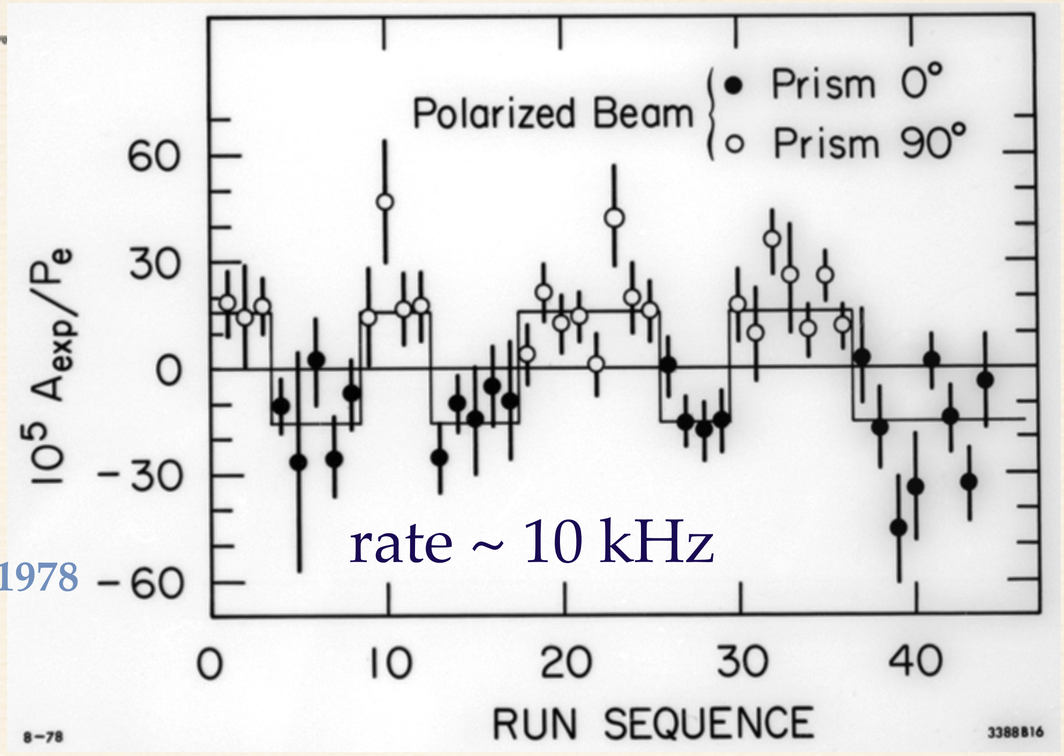
- **Flux Integration measures high rate without deadtime**



Does the weak neutral current amplitude interfere with the electromagnetic amplitude?

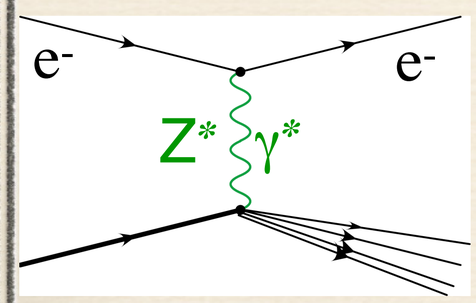
SLAC E122 Result





rate ~ 10 kHz

C.Y. Prescott et al, 1978

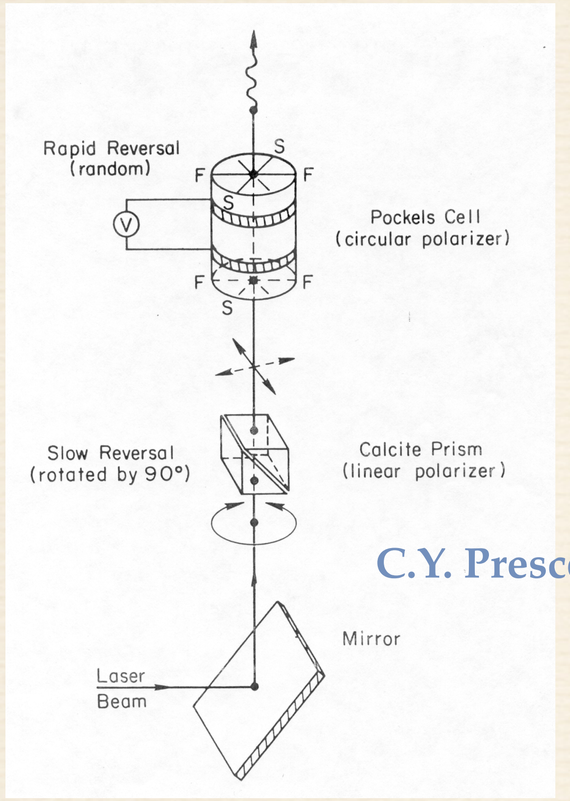


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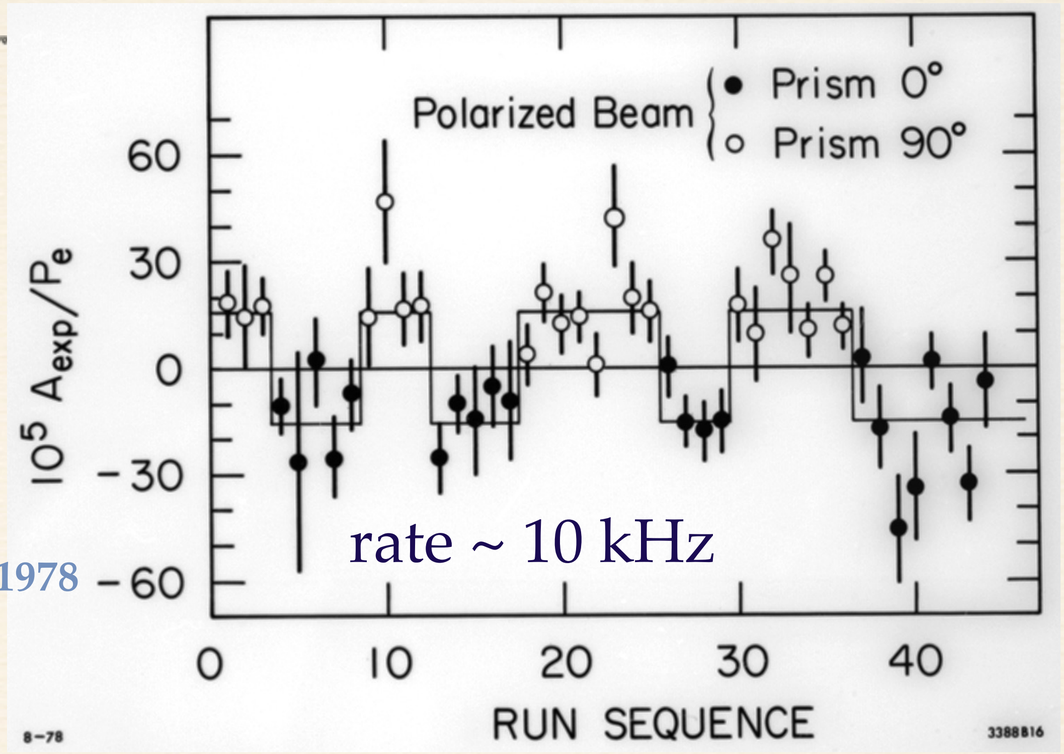
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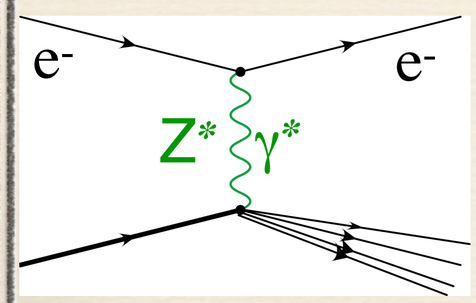
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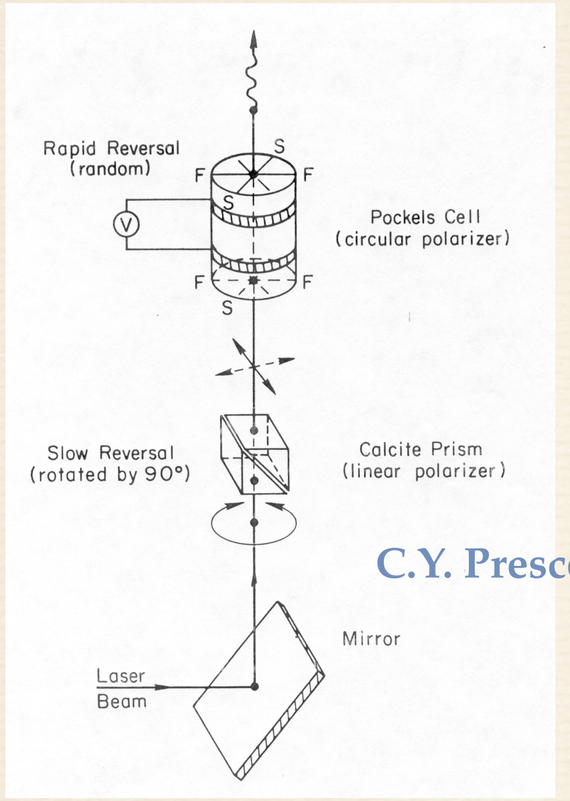
- ***Parity Violation in Weak Neutral Current Interactions***
- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

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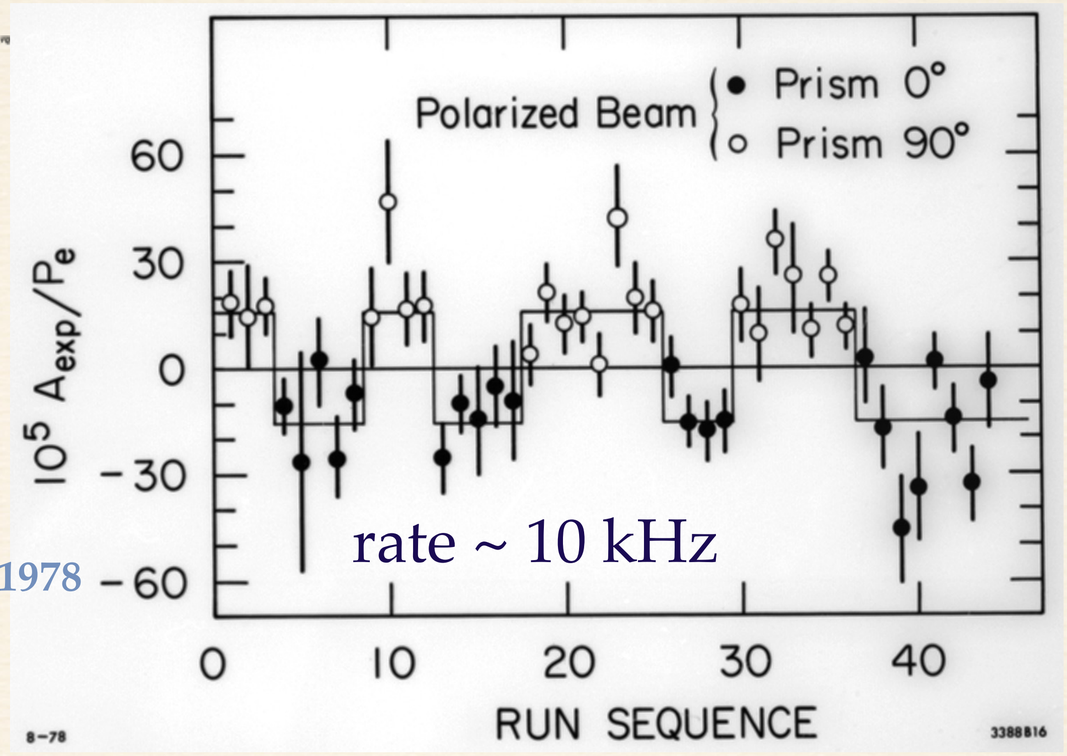
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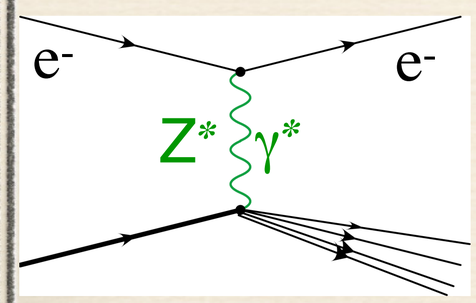
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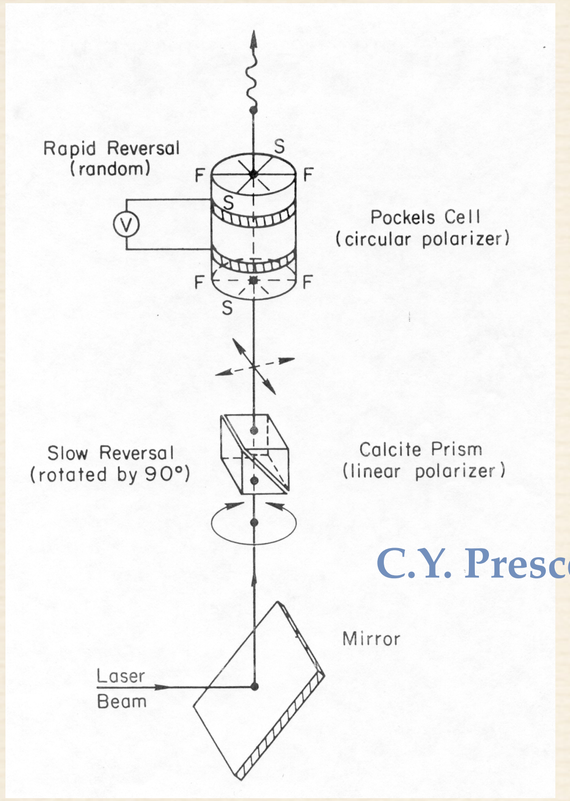
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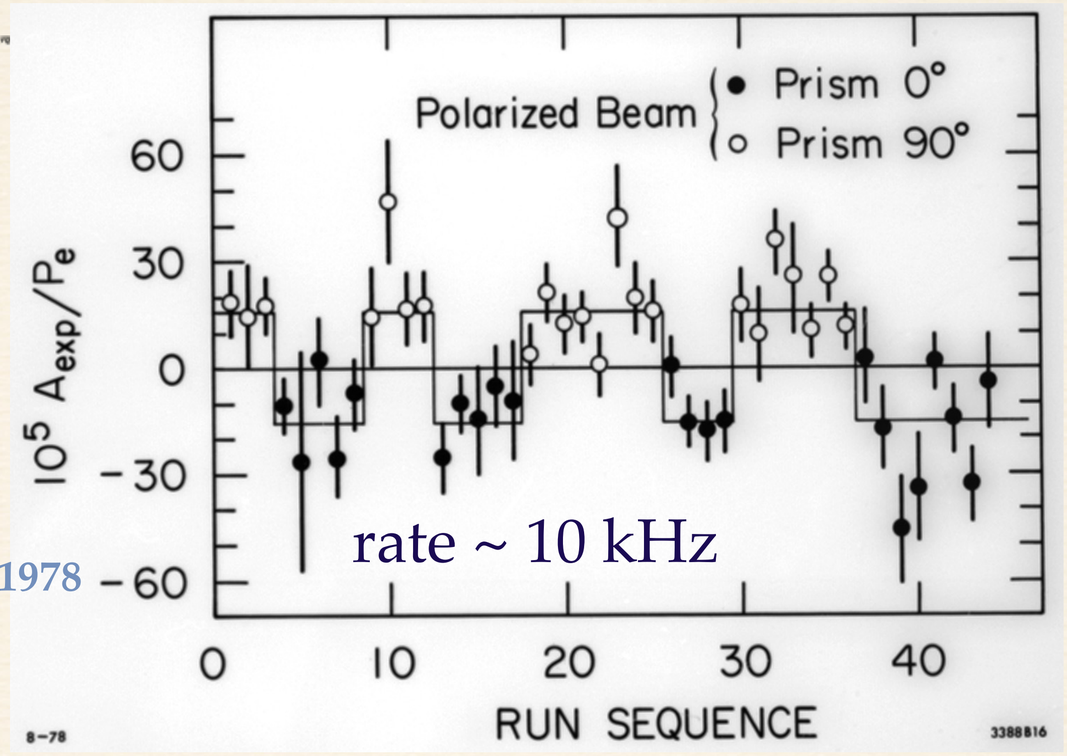
Glashow, Weinberg, Salam Nobel Prize awarded in 1979

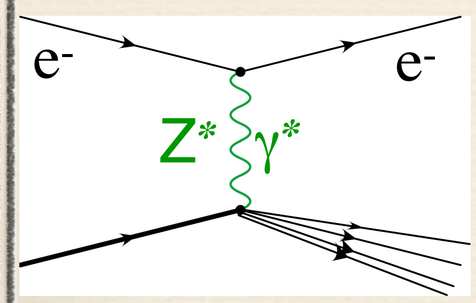
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C.Y. Prescott et al, 1978





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Nobel Press Release
October 15, 1979

"…Of special interest is a result, published in the summer of 1978, of an experiment at the electron accelerator at SLAC in Stanford, USA. In this experiment the scattering of high energy electrons on deuterium nuclei was studied and an effect due to a direct interplay between the electromagnetic and weak parts of the unified interaction could be observed…"

1980's **The ideas began at the same time as SLAC E122 but took much longer to complete**

Standard Model Tests on Nuclear Targets

Elastic scattering from $(J^\pi, T) = (0^+, 0)$ *nuclei* *Feinberg (1975)*

For a simple nucleus like ^{12}C, A_{PV} in elastic scattering at forward angle insensitive to nuclear structure: clean measurement of $\sin^2\theta_W$

^{12}C at MIT-Bates: $A_{PV} = (1.69 \pm 0.39 \pm 0.06) \times 10^{-6}$ *Souder (1990)*

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Quasi-elastic backward angle scattering from ^{9}Be

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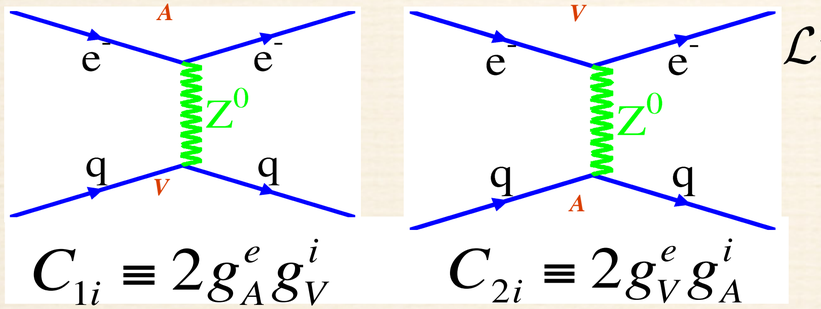
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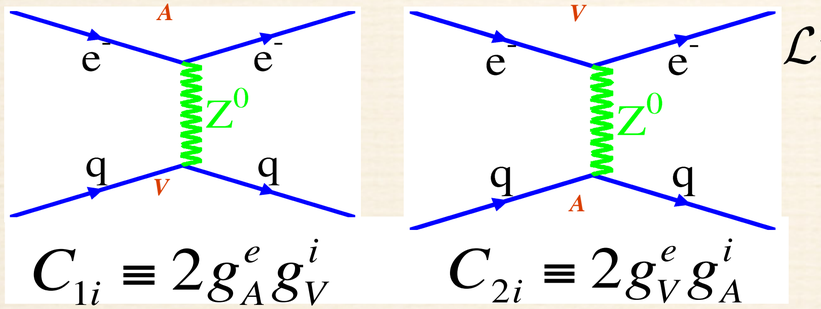
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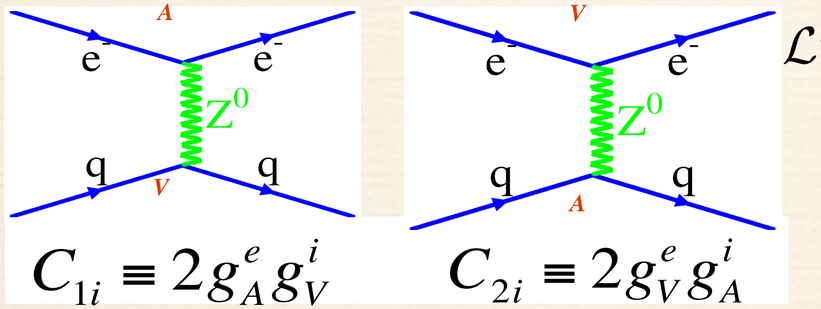
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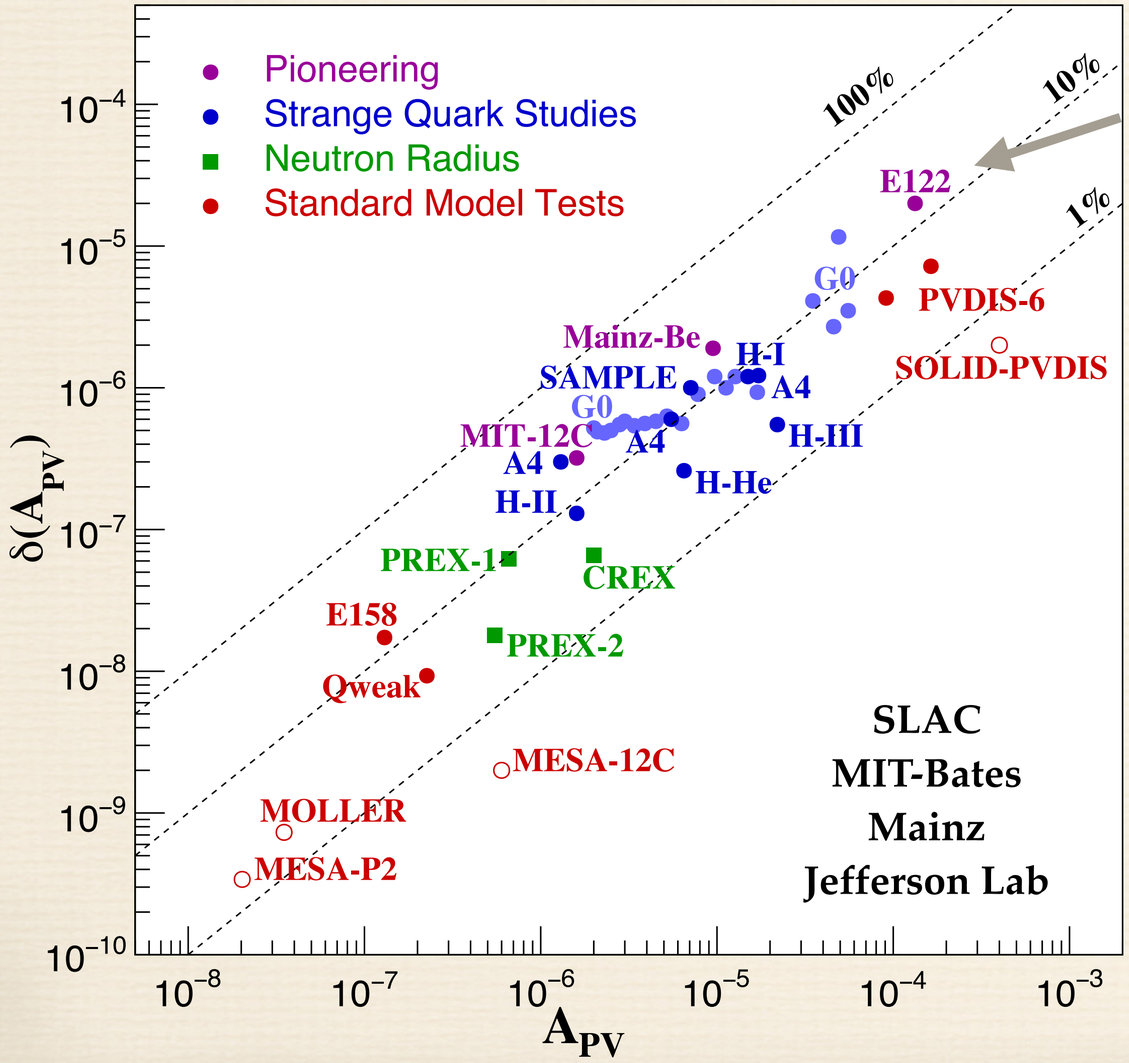
100 ppb systematics

100's of MHz rates

Continuous interplay between probing hadron structure and electroweak physics

5 Decades of Progress

Parity-violating electron scattering has become a precision tool



Pioneering electron-quark PV DIS experiment SLAC E122

State-of-the-art:

- *sub-part per billion statistical reach and systematic control*
- *sub-1% normalization control*

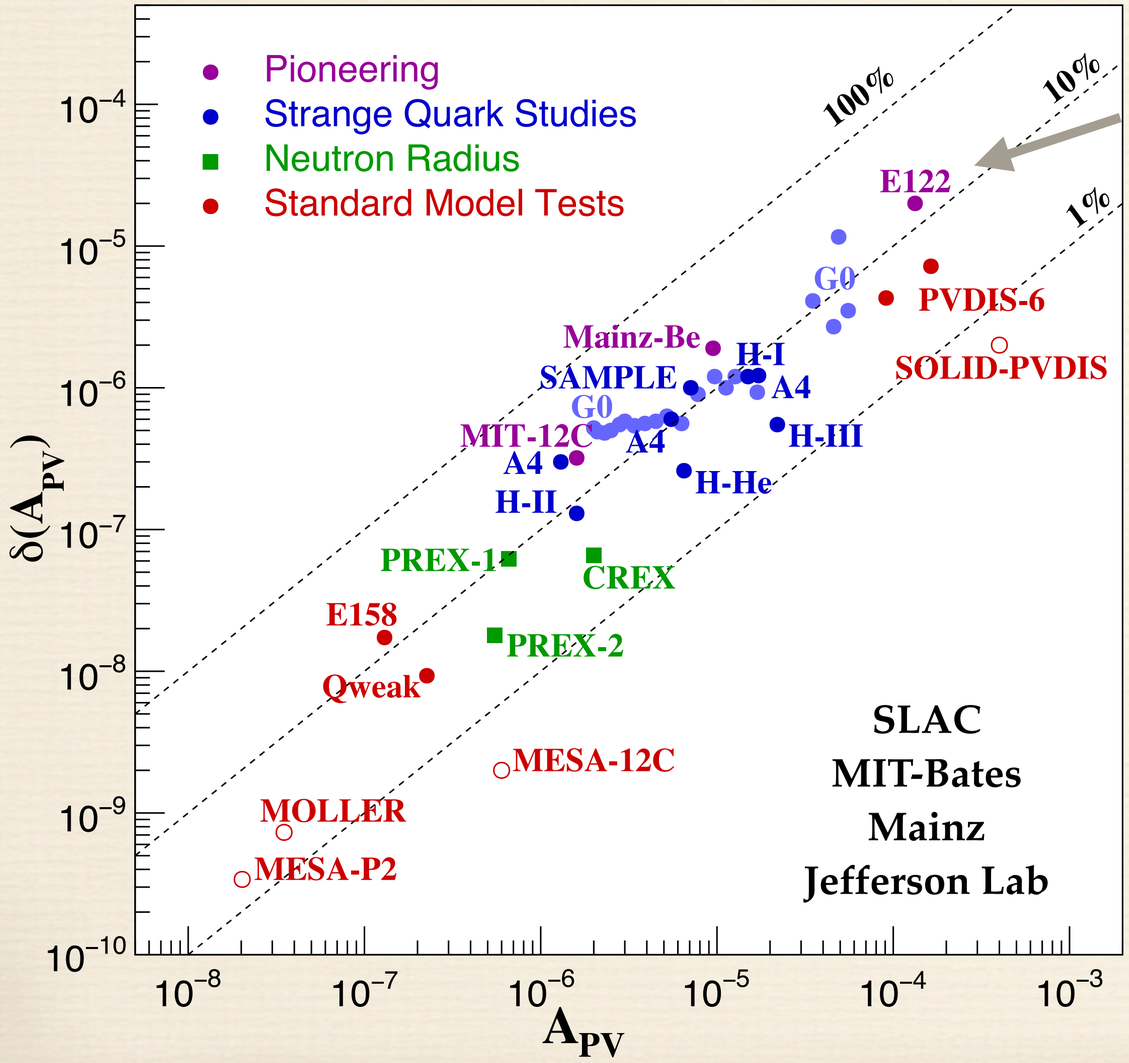
Remainder of the First Lecture

- *SLAC E158*
- *JLab Qweak (Hall C) and PVDIS (Hall A)*
- *Future Plans*

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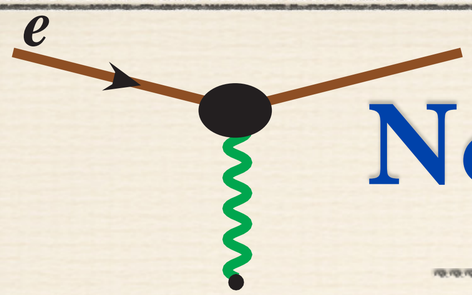
photocathodes, polarimetry, high power cryotargets, novel spectrometer concepts, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

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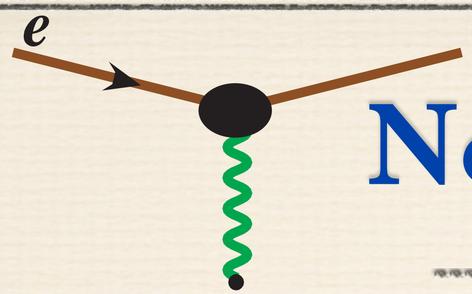
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New Electron Operators

- **Violation of Lepton Number**
  - Neutrinoless Double-Beta Decay?
- **Violation of Time Reversal Symmetry**
  - Non-zero Electric Dipole Moment of the Electron?
- **Violation of Charged Lepton Flavor**
  - muon-to-electron conversion in muon decay or nuclear muon capture?
- **Violation of Parity with Flavor Conservation**
  - new contributions to parity-violating electron scattering?



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$\frac{1}{\Lambda}\mathcal{L}_5$ 10^{15} GeV

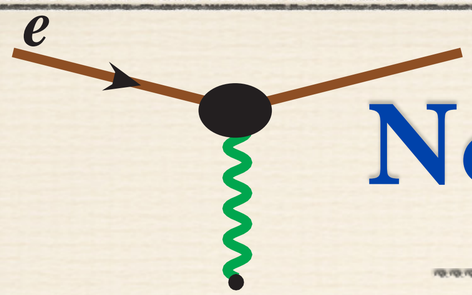
$\frac{1}{\Lambda^5}\mathcal{L}_9$ multi-TeV

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$\frac{1}{\Lambda^2}\mathcal{L}_6$ 100s of TeV

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Modern Day Electroweak Physics

New Electron Operators

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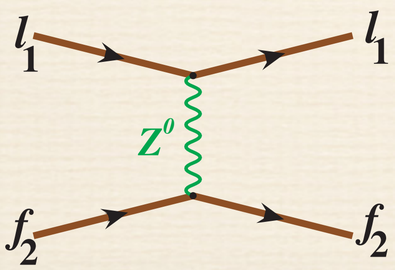
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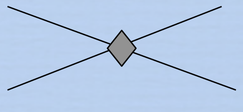
★ new contributions to parity-violating electron scattering?

multi-TeV

Search for new flavor-diagonal superweak forces



Look for tiny but measurable deviations from precisely calculable predictions for SM processes



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

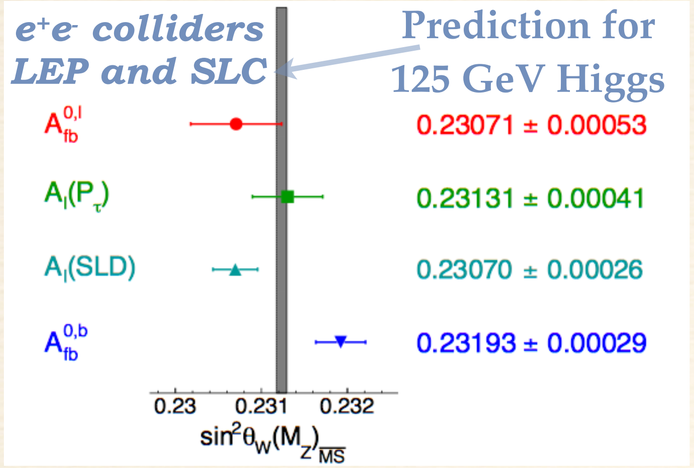
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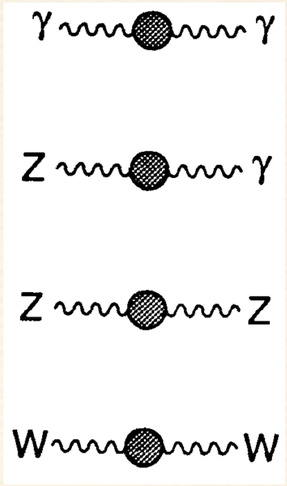
Mid-1990's

Measurements of $\sin^2\theta_W$

The most precise measurements are from LEP/SLC







S, T, U parameters

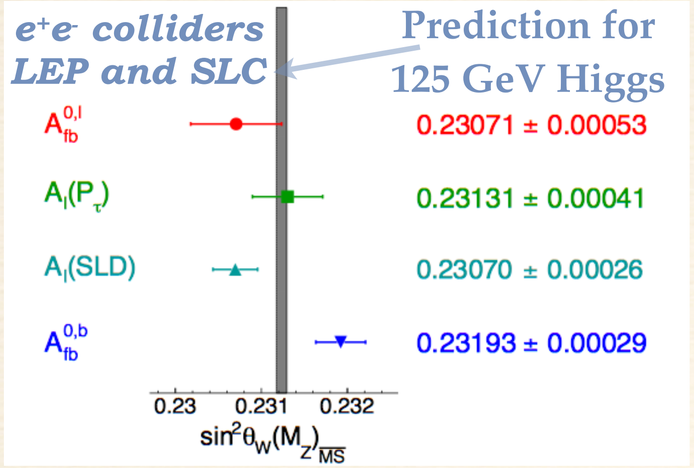
Stringent constraints on large classes of new physics models

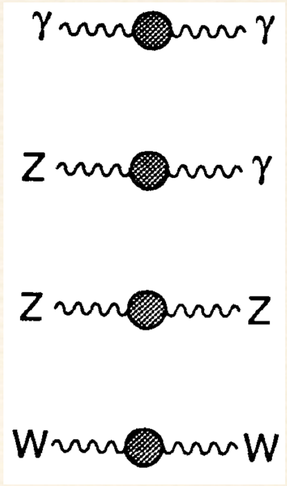
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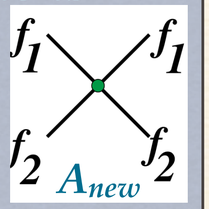
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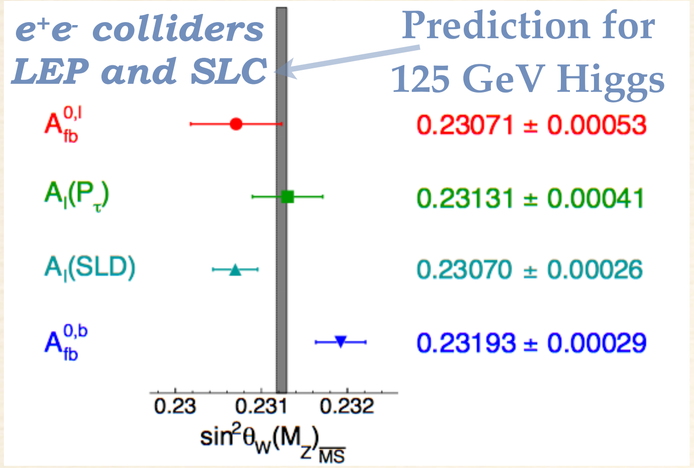
New heavy physics that does not couple directly to SM gauge bosons

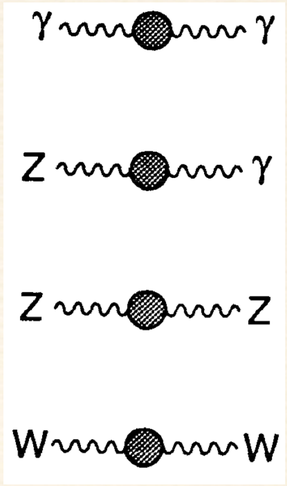
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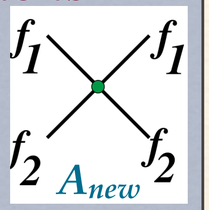
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$$\left|A_Z + A_{new}\right|^2 \to A_Z^2\left[1 + \left(\frac{A_{new}}{A_Z}\right)^2\right]$$

no interference!

New flavor diagonal interactions mediated by a new light boson such as the "dark Z"

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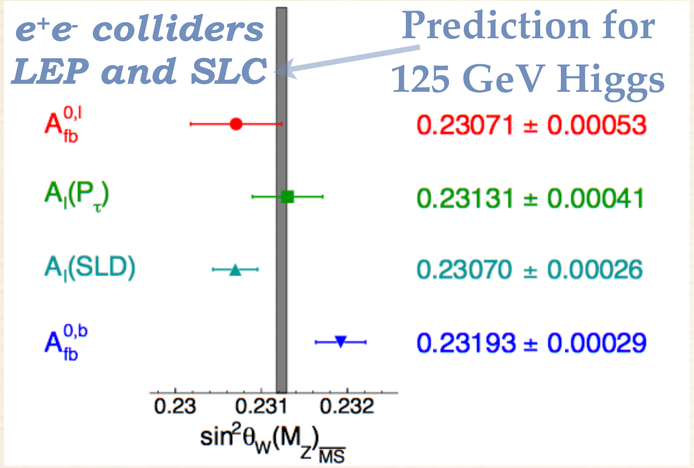
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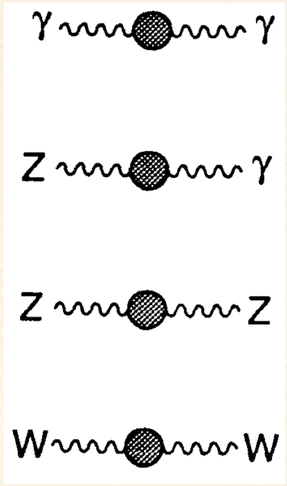
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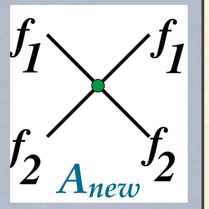
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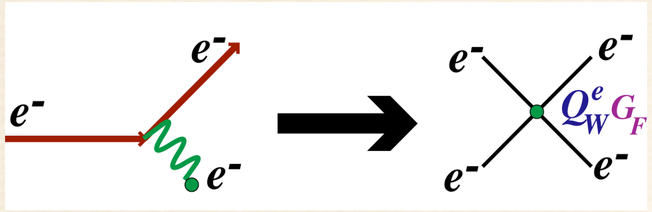
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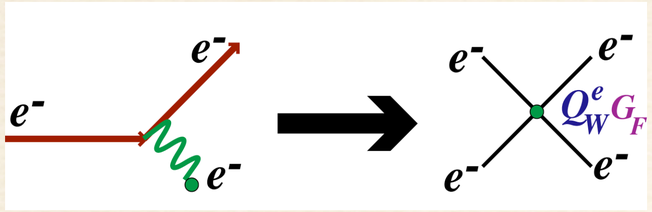
PV Electron-Electron (Møller) Scattering

A rare opportunity: a well-understood EW process below the scale of electroweak symmetry breaking that is purely leptonic



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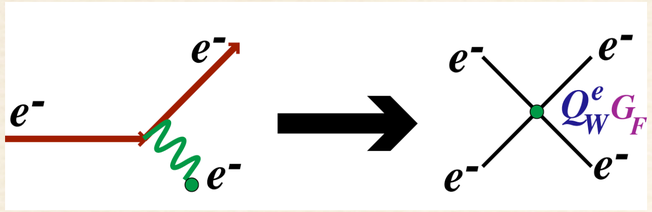
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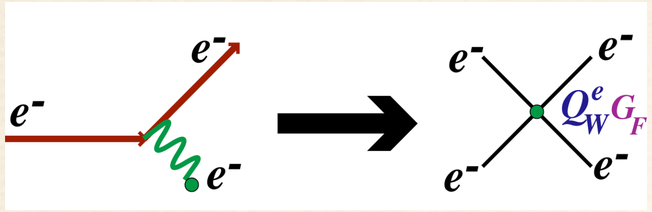
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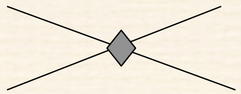
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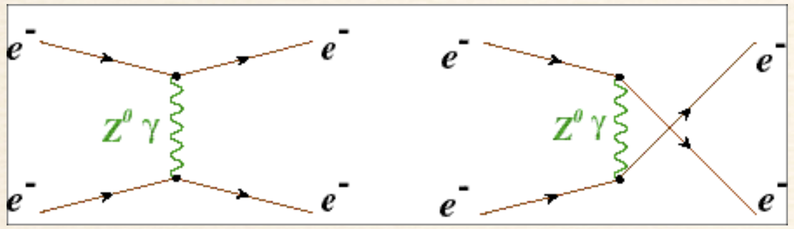
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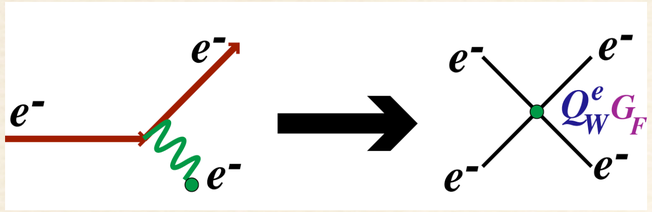


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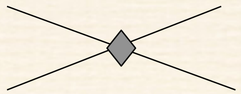
$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\rm new}\right|^2 \rightarrow \mathbf{A}_\gamma^2\left[1 + 2\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + 2\left(\frac{\mathbf{A}_{\rm new}}{\mathbf{A}_\gamma}\right)\right]$$

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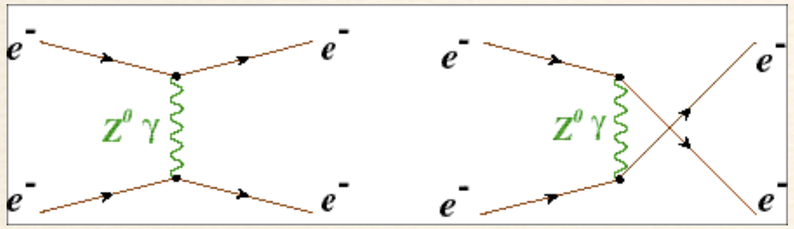
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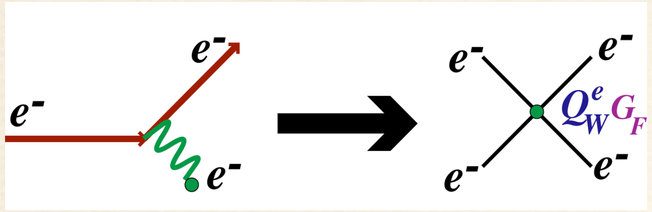
$$A_{PV} \approx 8\times10^{-8}\, E_{beam}(1-4\sin^2\vartheta_W)$$

$Q^2 = 2m_e E_{\text{beam}}$ ⇨ **Tiny!**

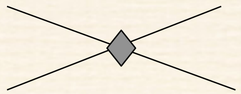
SLAC E158: First Measurement of the Electron's Weak Charge

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+

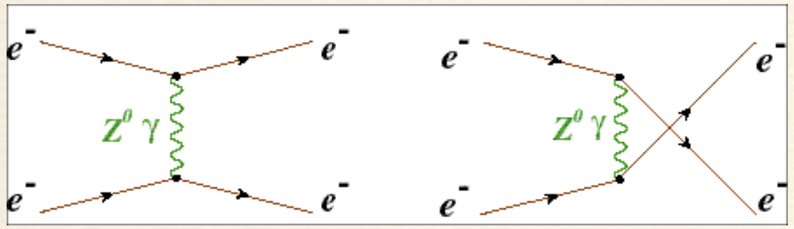


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

electron target:

$$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$



$$\left|\mathbf{A_\gamma + A_Z + A_{new}}\right|^2 \rightarrow \mathbf{A_\gamma^2}\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A_\gamma}}\right) + \mathbf{2}\left(\frac{\mathbf{A_{new}}}{\mathbf{A_\gamma}}\right)\right]$$

$$A_{PV} \approx 8\times10^{-8}\, E_{beam}(1-4\sin^2\vartheta_W)$$

$$Q^2 = 2m_e E_{\text{beam}}$$

Tiny!



45 & 48 GeV Beam

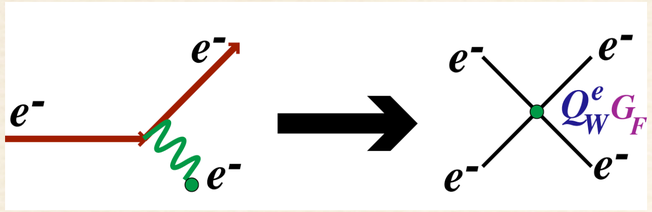
85% longitudinal polarization

End Station A at SLAC

SLAC E158: 1997-2004

PV Electron-Electron (Møller) Scattering

A rare opportunity: a well-understood EW process below the scale of electroweak symmetry breaking that is purely leptonic

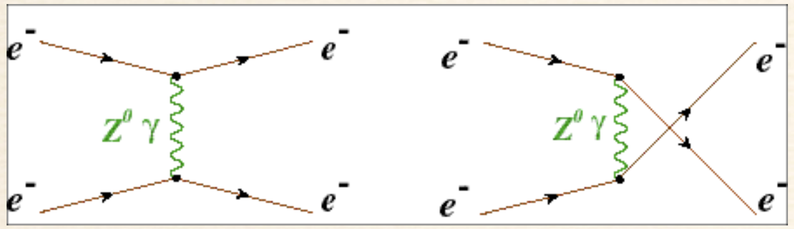


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End Station A at SLAC

SLAC E158: 1997-2004

A_{PV} ~ 200 parts per billion

Circa 2000's



SLAC End Station A

Circa 2000's

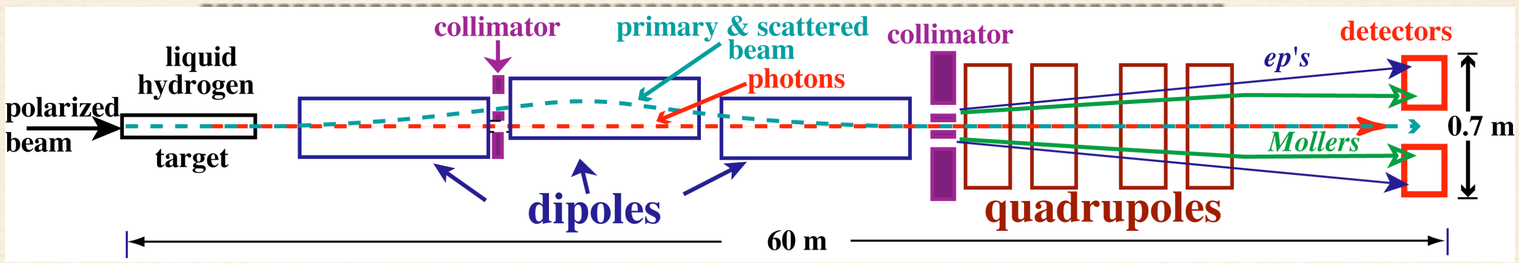


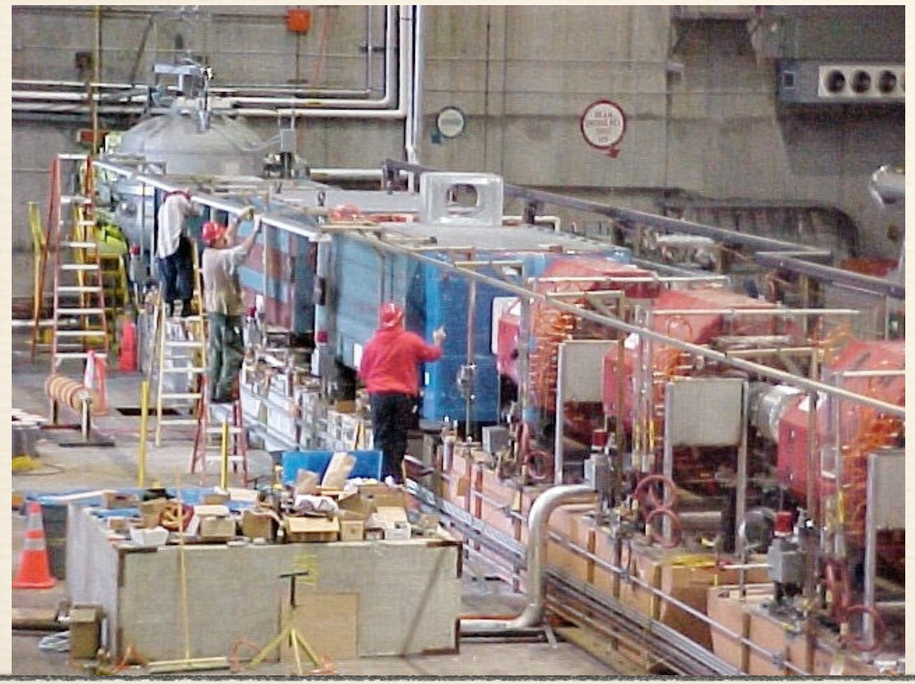
SLAC End Station A

Goal: error small enough to probe TeV scale physics

SLAC E158 Proposal 1997

~ 10 ppb statistical error at highest E_{beam}, ~ 0.5% error on weak mixing angle



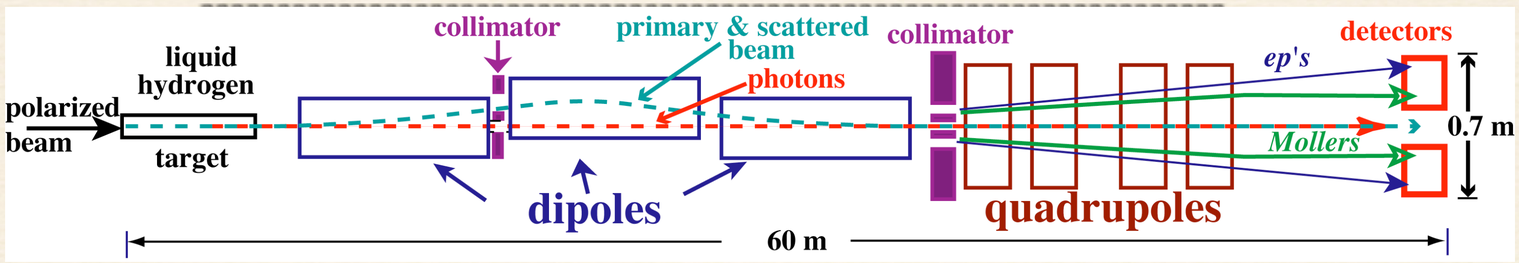


- **10 nm control of beam centroid on target**
  - R&D on polarized source laser transport elements
- **12 microamp beam current maximum**
  - 1.5 meter Liquid Hydrogen target
- **20 Million electrons per pulse @ 120 Hz**
  - 200 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 10^{-4}*
    - *Pulse-to-pulse monitoring resolution ~ 1 micron*
    - *Pulse-to-pulse beam fluctuations < 100 microns*
  - 100 Mrad radiation dose from scattered flux
    - *State-of-the-art radiation-hard integrating calorimeter*
- **Full Azimuthal acceptance with θ_{lab} ~ 5 mrad**
  - Quadrupole spectrometer
  - Complex collimation and radiation shielding issues

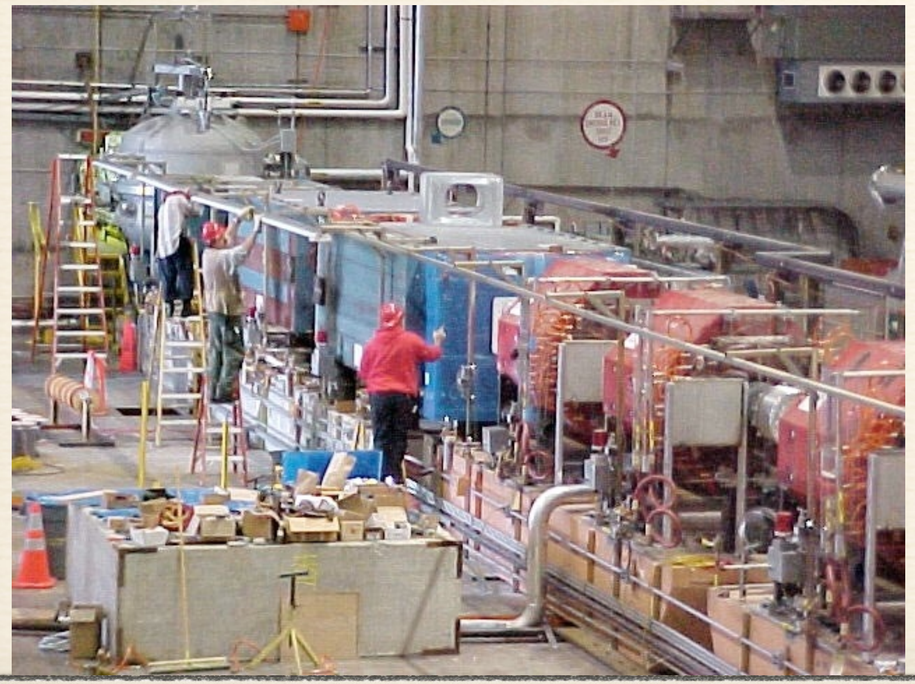
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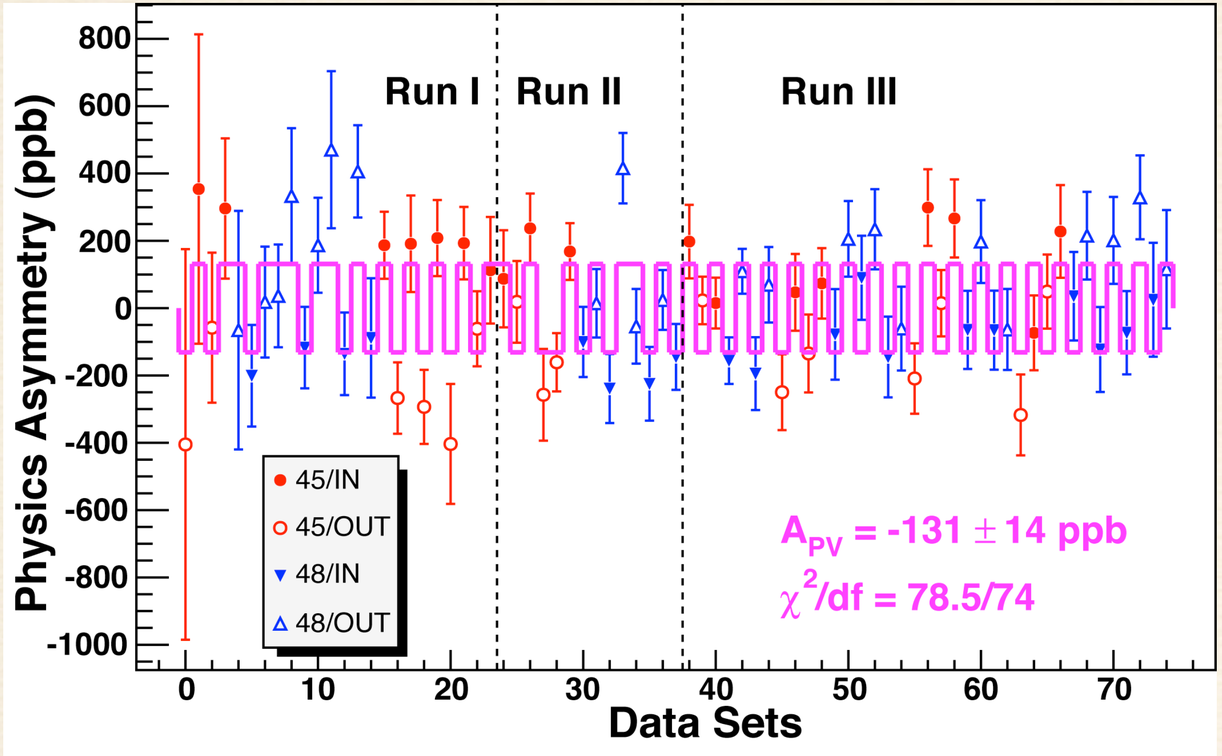
A large number of technical challenges



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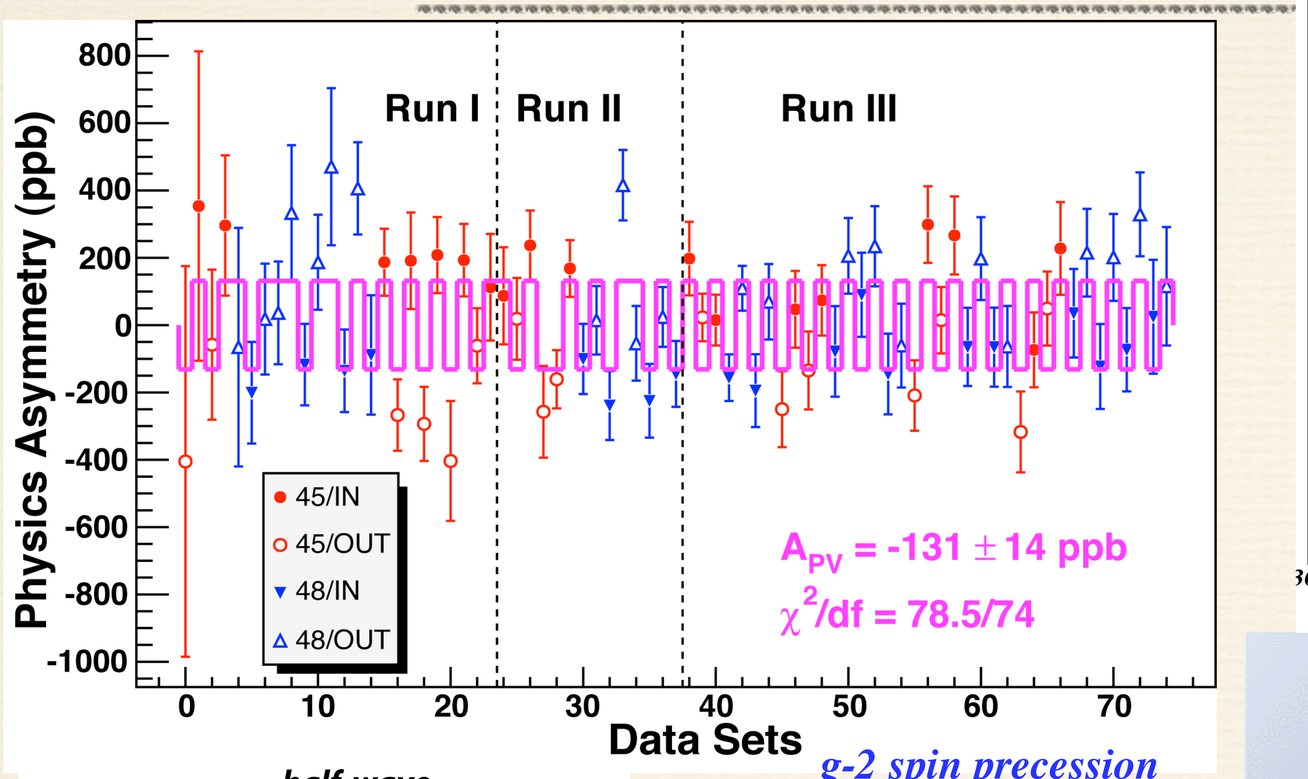
~60 physicists, 8 Ph.D. Students

E158 Physics Data 2002-3



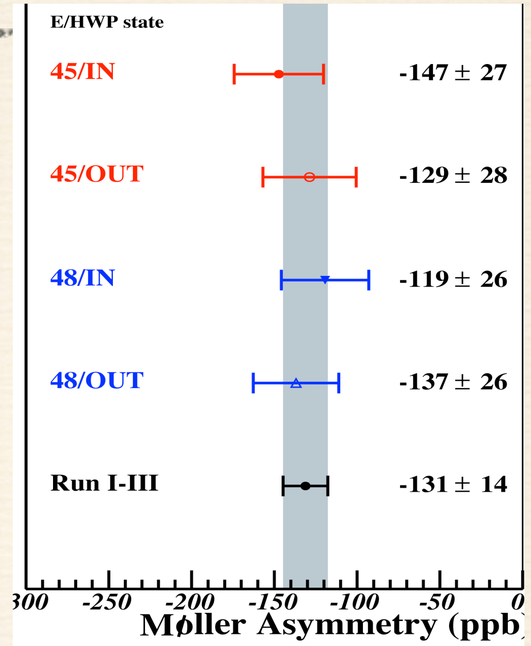
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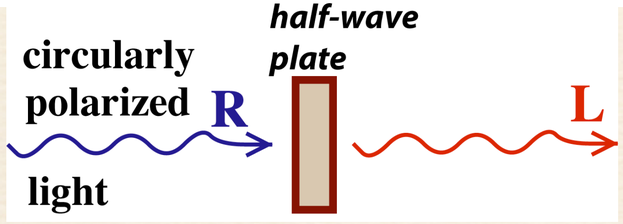
E158 Physics Data 2002-3



A_{PV} = -131 ± 14 ppb

χ^2/df = 78.5/74

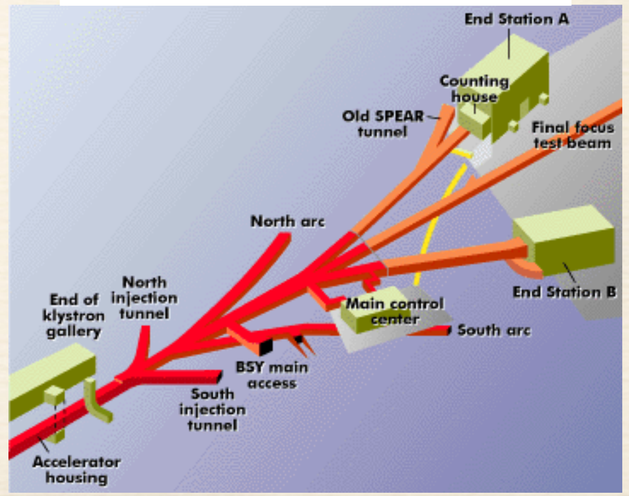




g-2 spin precession

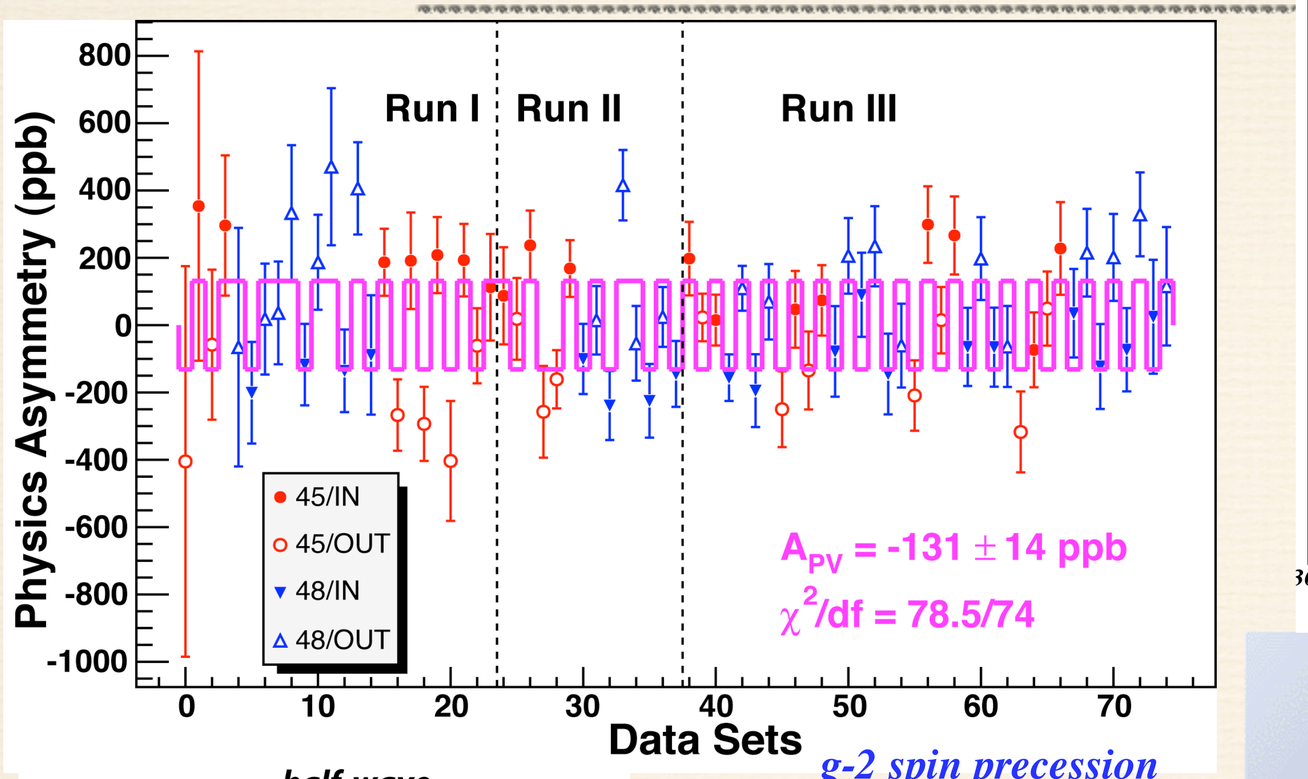
45 GeV: 14.0 revs

48 GeV: 14.5 revs



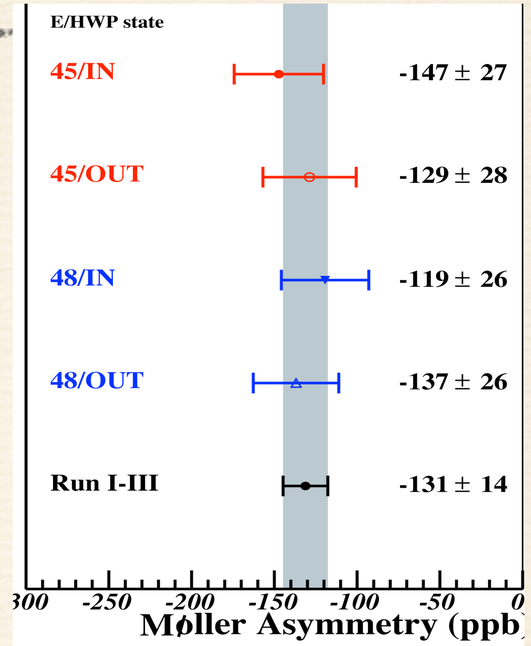
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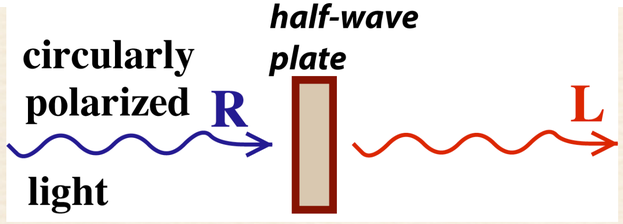
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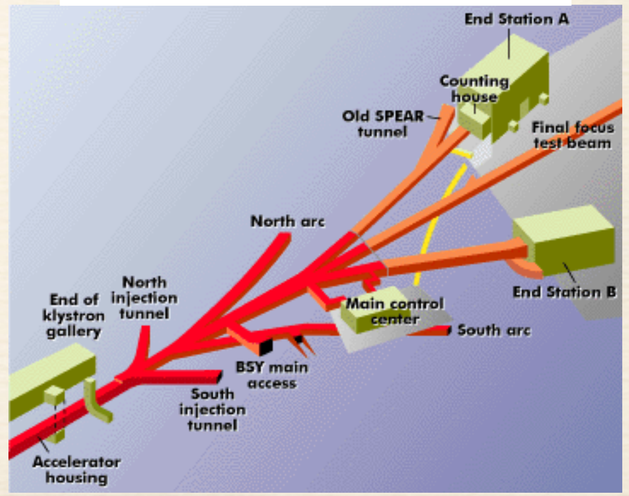




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$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Phys. Rev. Lett. **95** 081601 (2005)

Tree-level prediction: ~ 250 ppb

E158 Implications

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Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

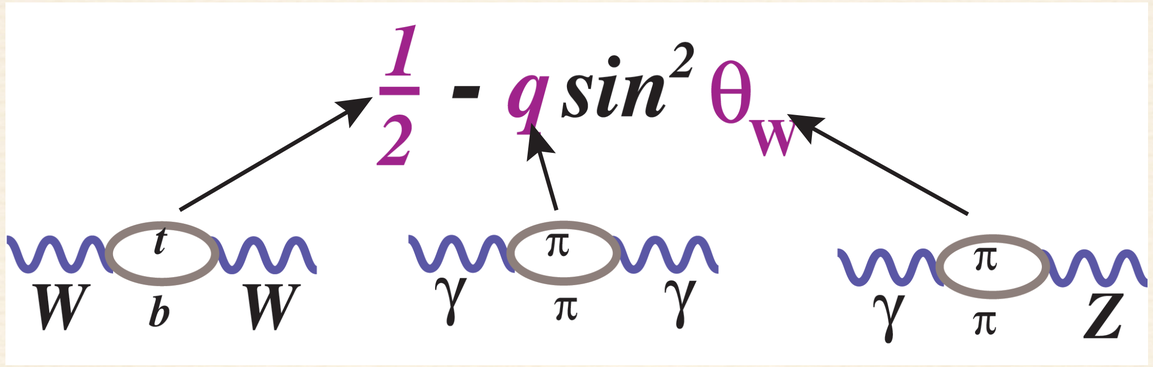
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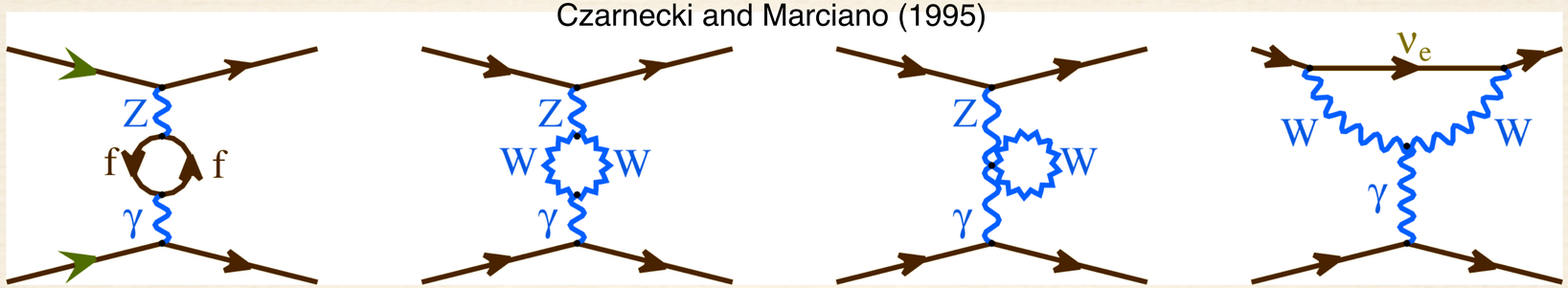
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Czarnecki and Marciano (1995)



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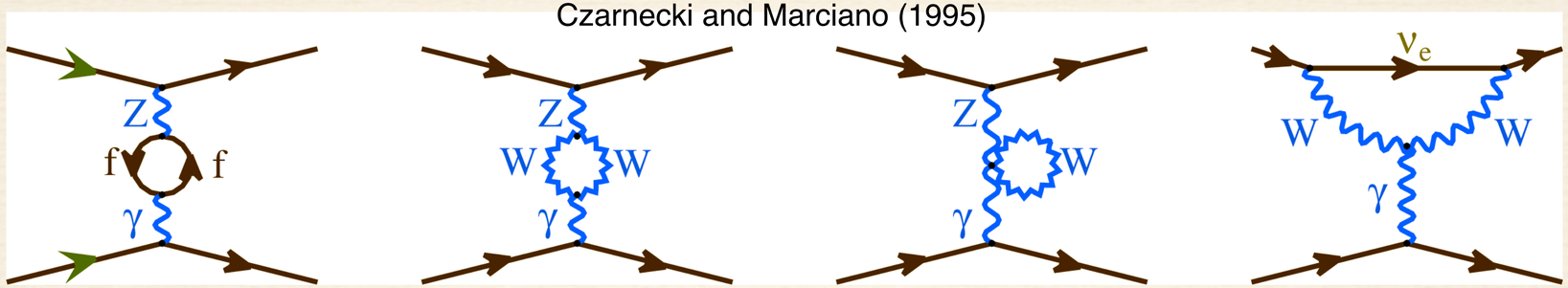
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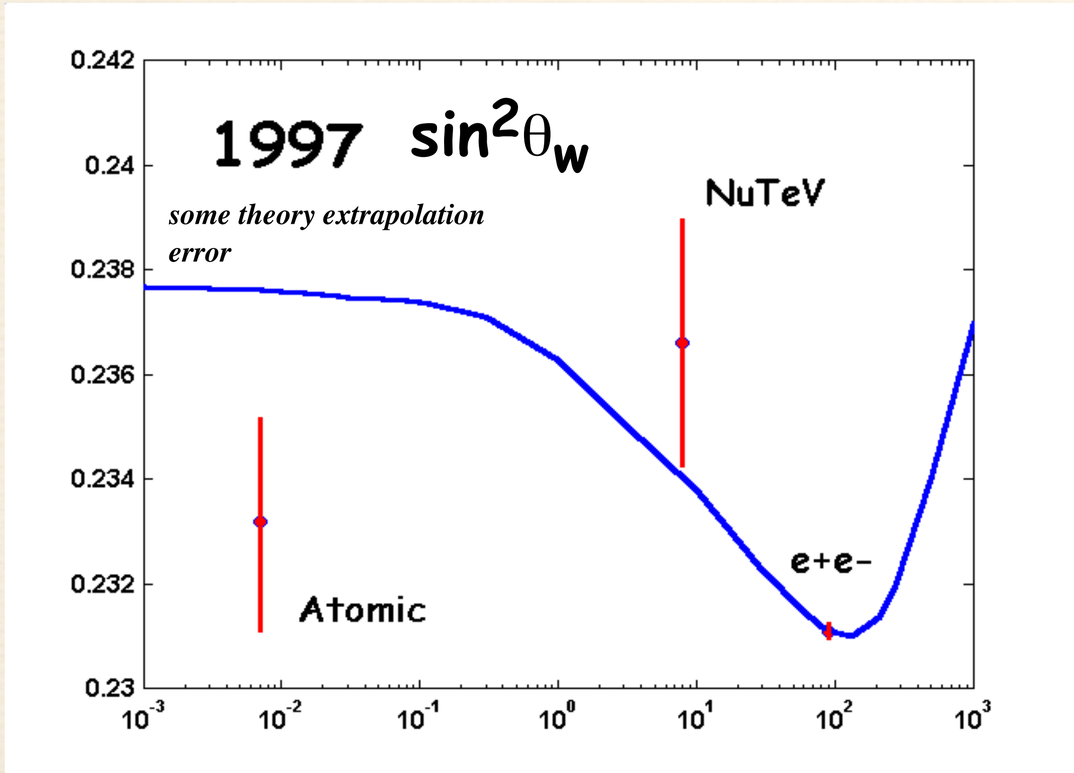
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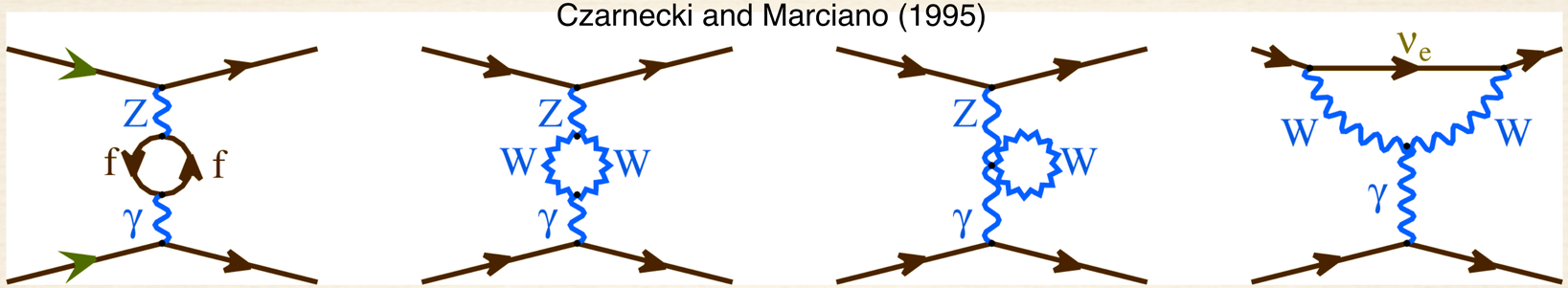
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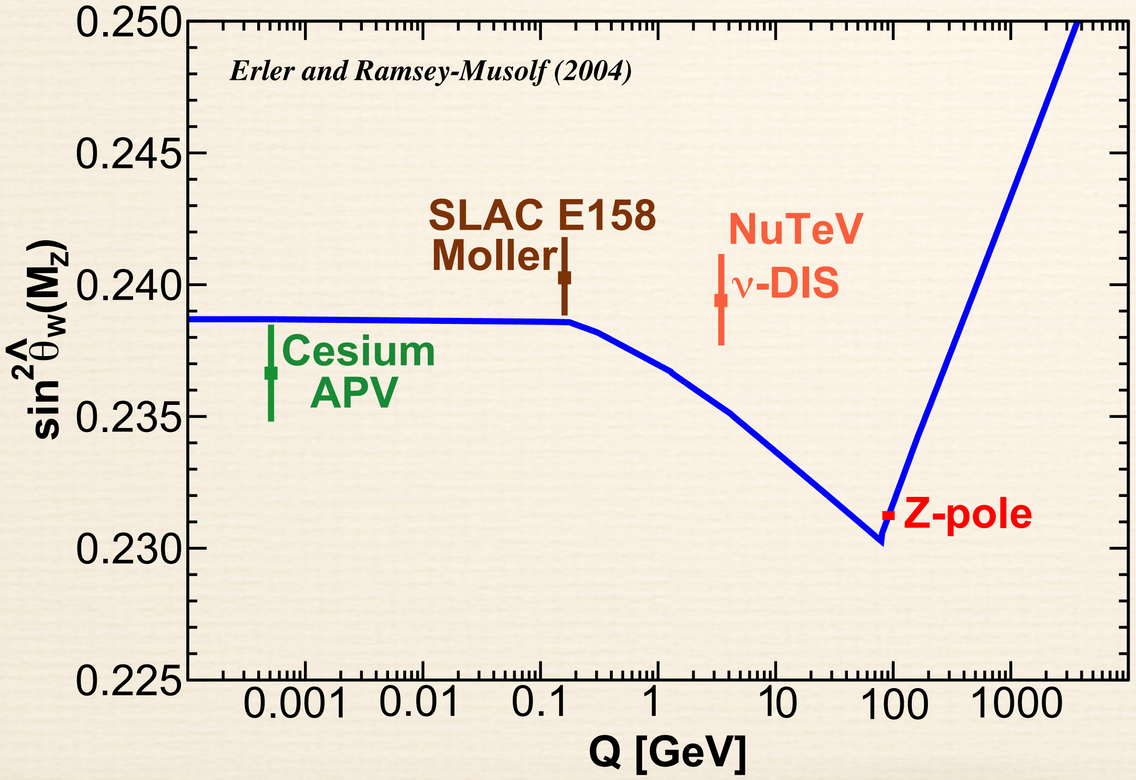
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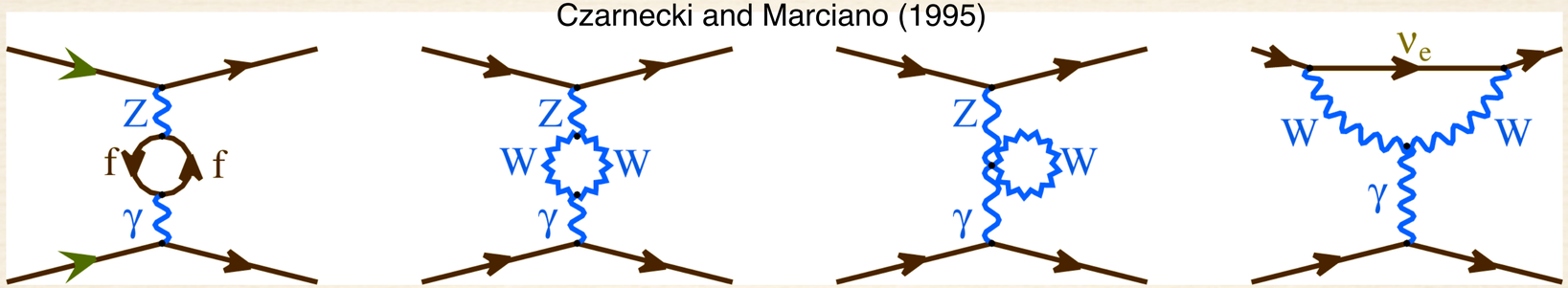
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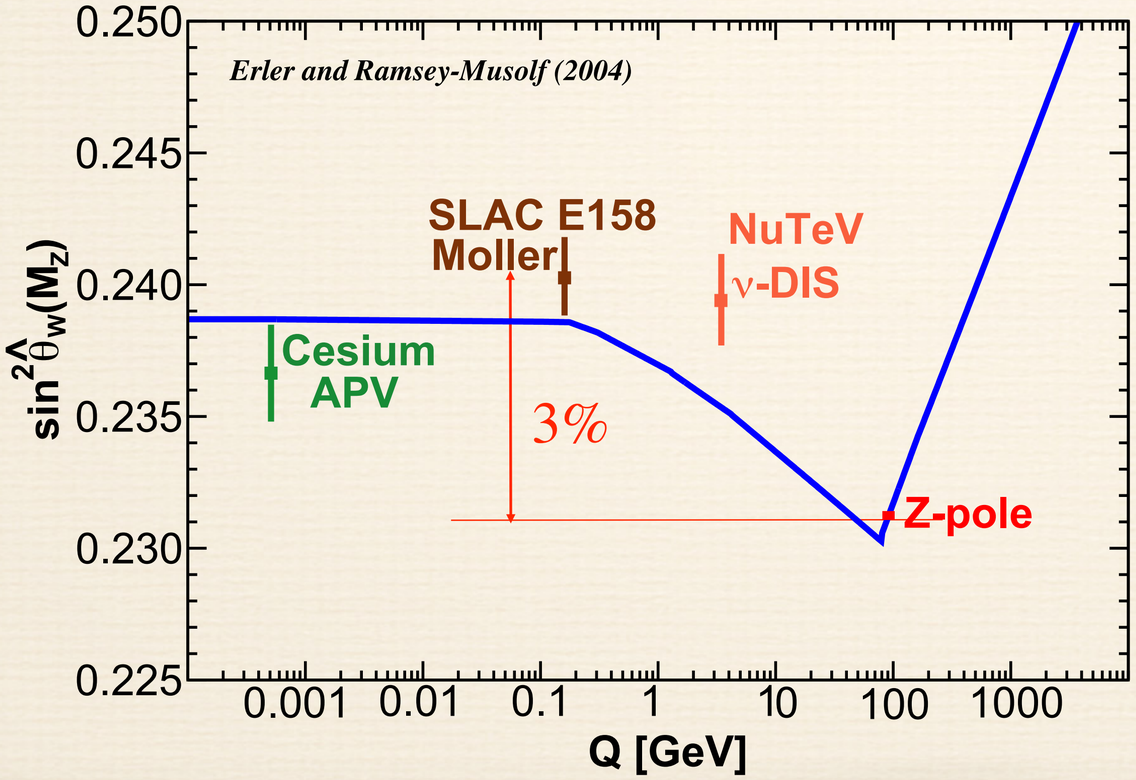
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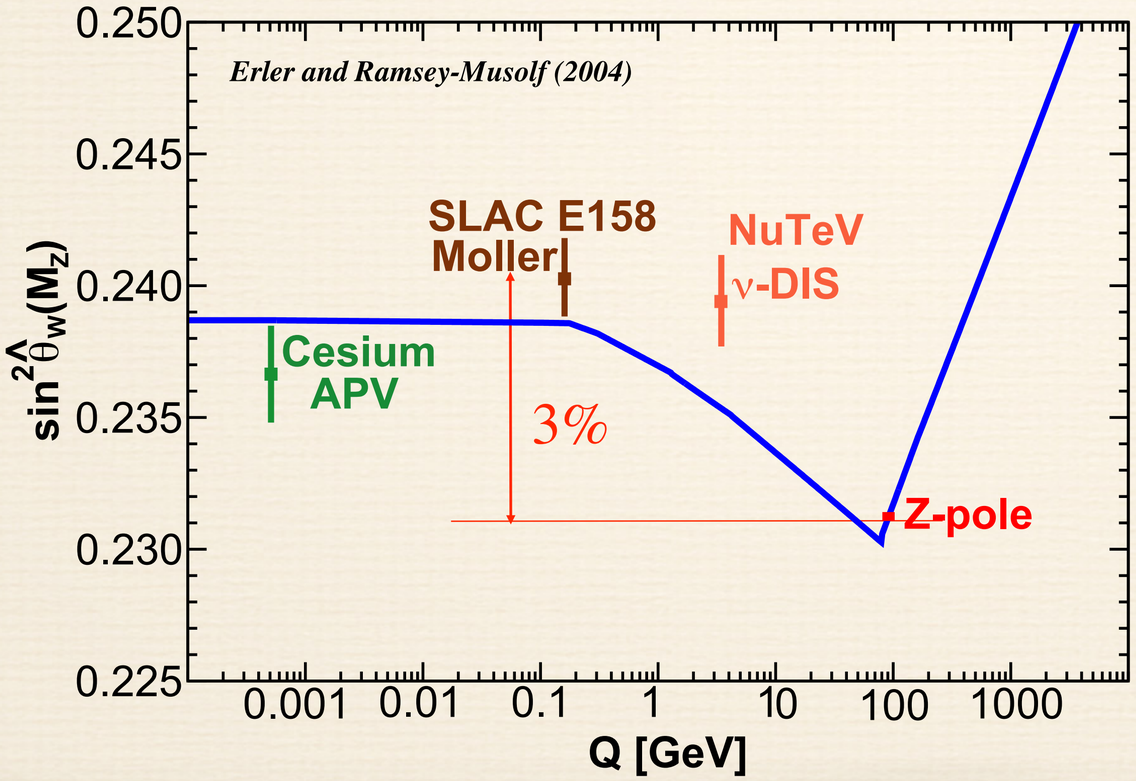
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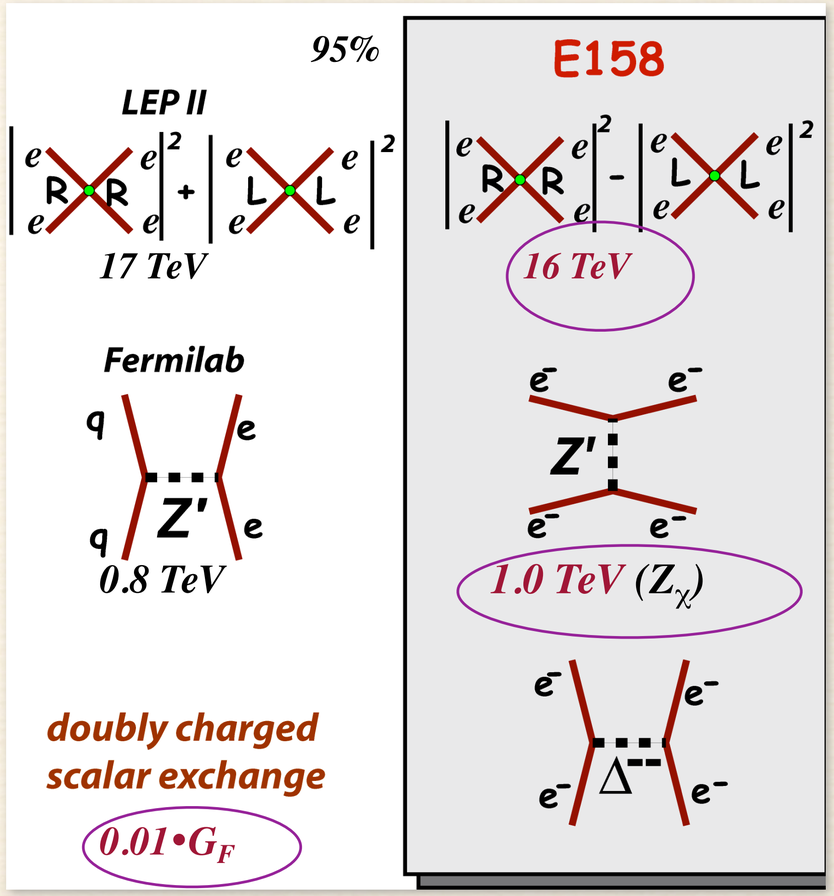
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Limits on "New" Physics



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Nature
Vol 435 26 May 2005

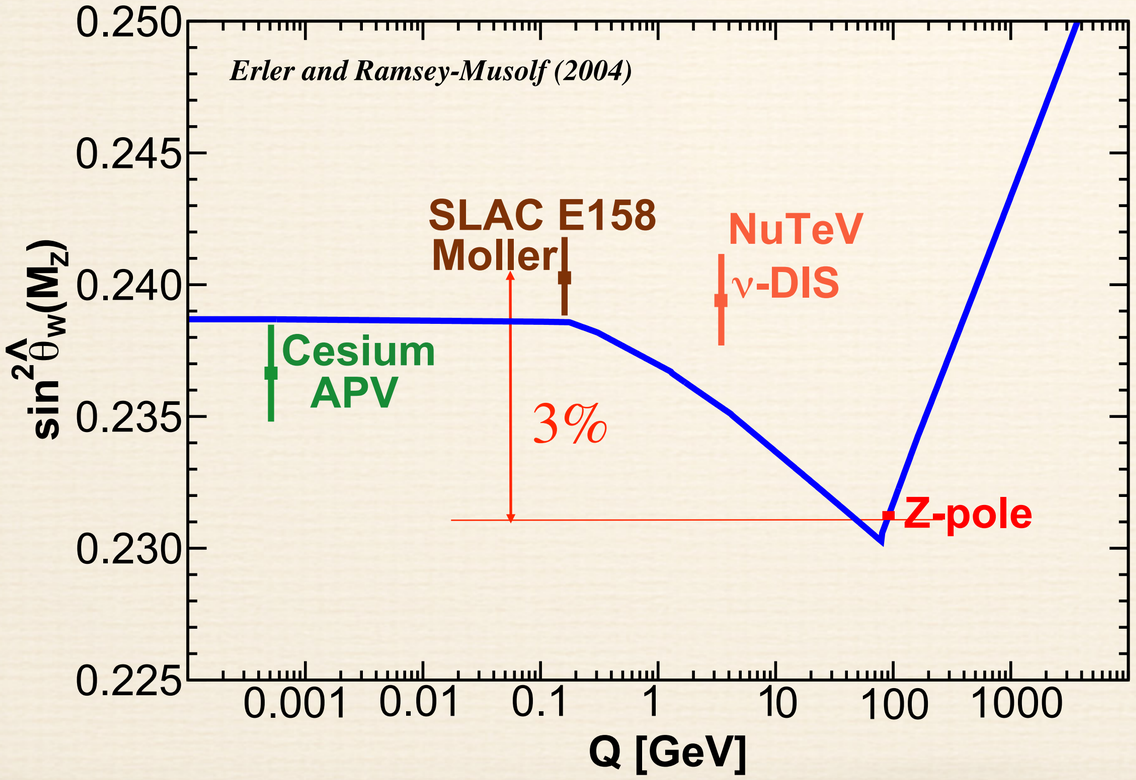
NEWS AND VIEWS

PARTICLE PHYSICS

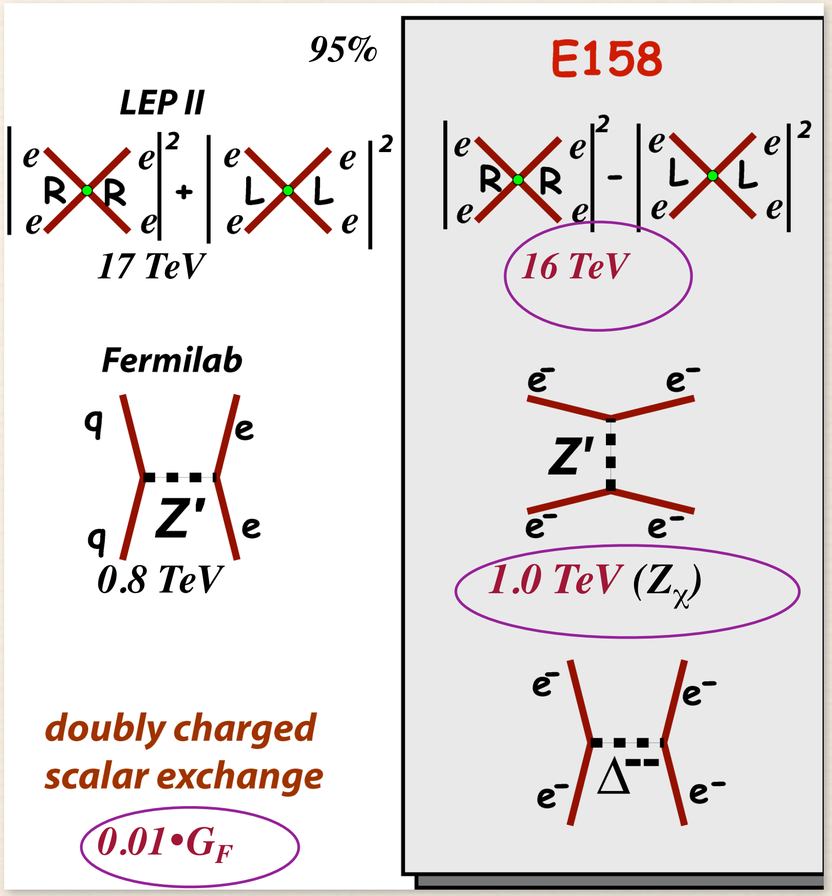
Electrons are not ambidextrous

Andrzej Czarnecki and William J. Marciano

The best low-energy measurement yet obtained of the electroweak mixing angle — a central parameter of the standard model of particle physics — is the last hurrah for Stanford's powerful two-mile linear accelerator.



Limits on "New" Physics

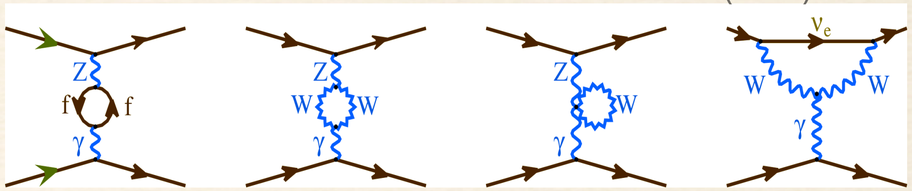


Thumb Rule: Weak mixing angle must be measured to sub-0.5% precision

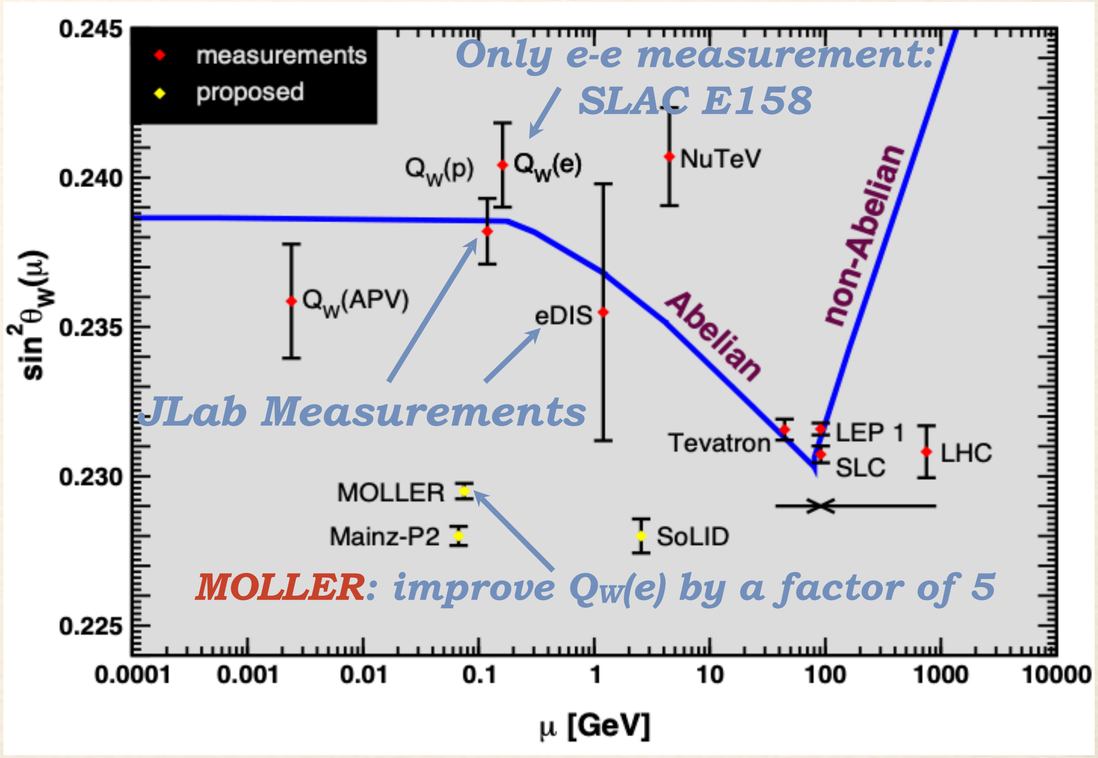
WNC "Bookkeeping"

Electroweak Radiative Corrections causes weak mixing angle to "run"

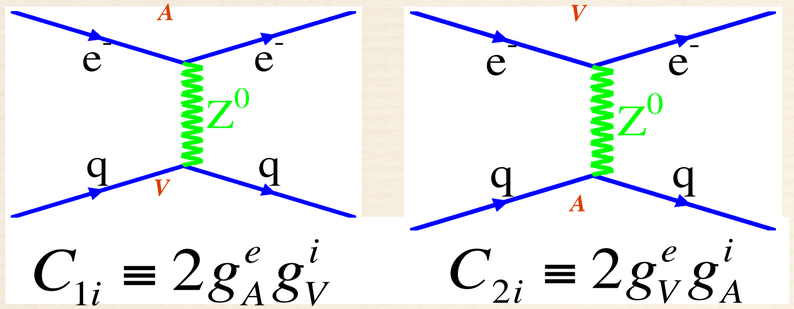
Czarnecki and Marciano (1995)



- **Atomic Parity Violation: Cs-133**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering: NuTeV**
  - future measurements and theory challenging
- **PV Møller Scattering: E158 at SLAC**
  - statistics limited, theory robust
  - next generation: MOLLER (factor of 5 better)
- **PV elastic e-p scattering: Qweak**
  - theory robust at low beam energy
  - next generation: P2 (factor of 3 better)
- **PV Deep Inelastic Scattering: PVDIS**
  - theory robust for ^{2}H in valence quark region
  - factor of 5 improvement: SOLID



Weak Neutral Current (WNC) Couplings

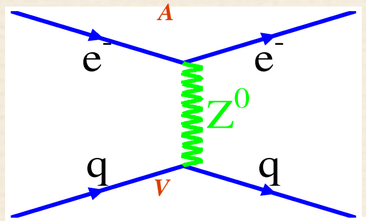


$C_{1i} \equiv 2 g_A^e g_V^i$

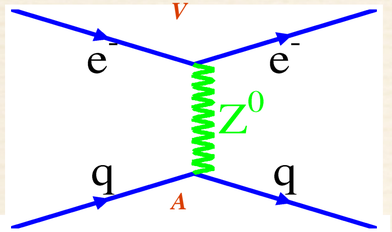
$C_{2i} \equiv 2 g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

Weak Neutral Current (WNC) Couplings



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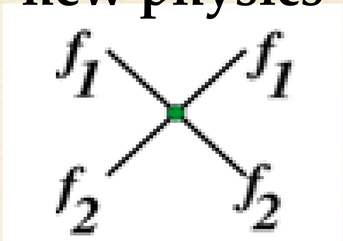
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$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

$$\begin{array}{lcll} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx 0.04 \end{array}$$

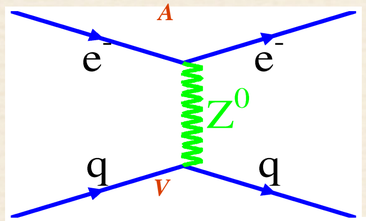
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new physics

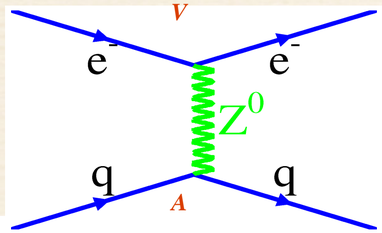


$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

Weak Neutral Current (WNC) Couplings



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$C_{2i} \equiv 2 g_V^e g_A^i$

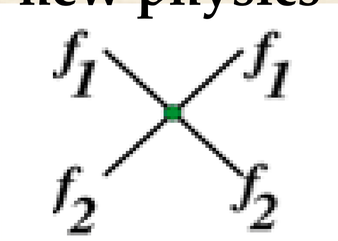
$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

C_{1u}	$= -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
C_{1d}	$= \frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$\approx$	0.35
C_{2u}	$= -\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
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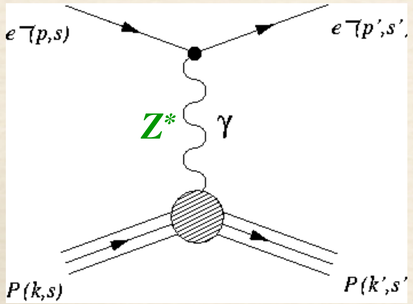
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

⇨ ***PV elastic e-N scattering, Atomic parity violation***

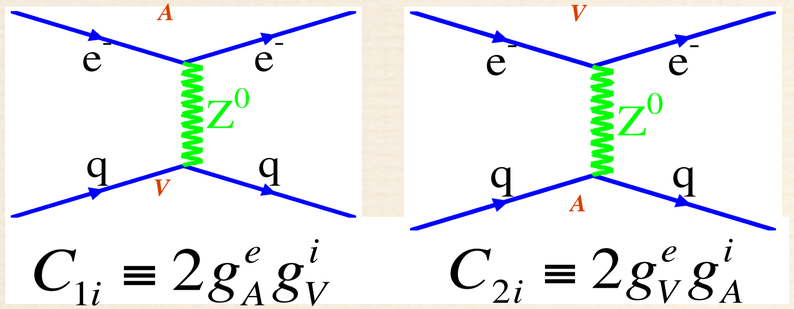
+ new physics



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$



Weak Neutral Current (WNC) Couplings



$$C_{1i} \equiv 2 g_A^e g_V^i$$

$$C_{2i} \equiv 2 g_V^e g_A^i$$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

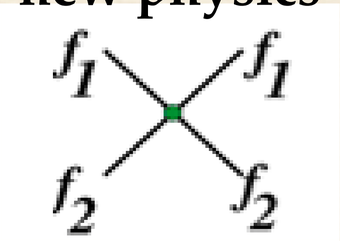
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$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ ⇨ ***PV elastic e-N scattering, Atomic parity violation***

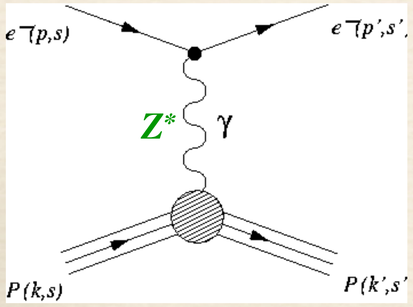
$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ ⇨ ***PV deep inelastic scattering***

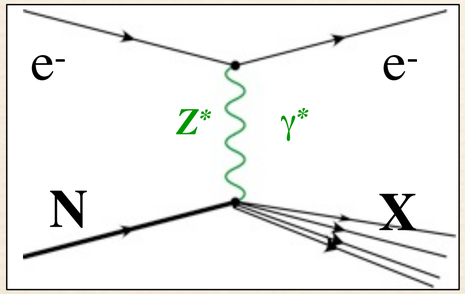
+

new physics

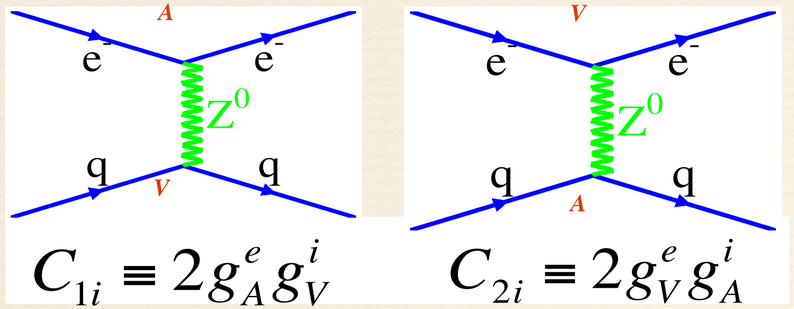


$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$





Weak Neutral Current (WNC) Couplings



$C_{1i} \equiv 2 g_A^e g_V^i$

$C_{2i} \equiv 2 g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

$$\begin{array}{lcll} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx 0.04 \end{array}$$

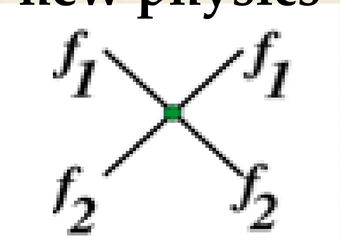
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$ ***PV elastic e-N scattering, Atomic parity violation***

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$ ***PV deep inelastic scattering***

$$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2 \Rightarrow$$ ***PV Møller scattering***

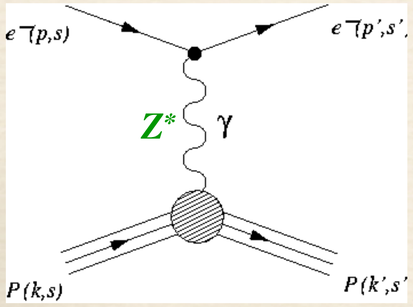
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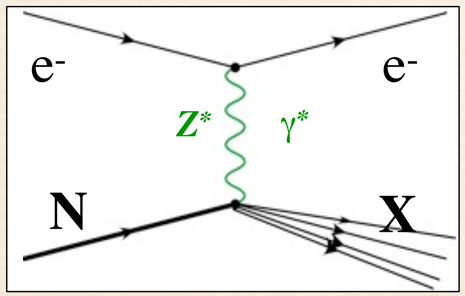
new physics



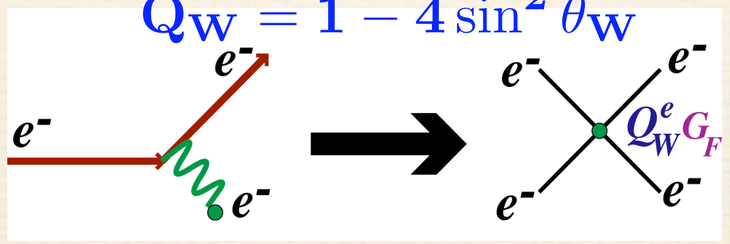
$$\mathcal{L}_{f_1 f_2} =$$

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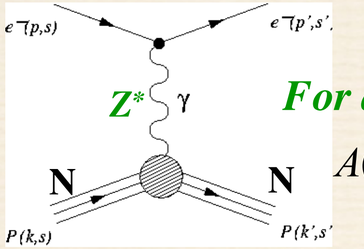
$Q_W = 1 - 4\sin^2\theta_W$



Past JLab Experiments

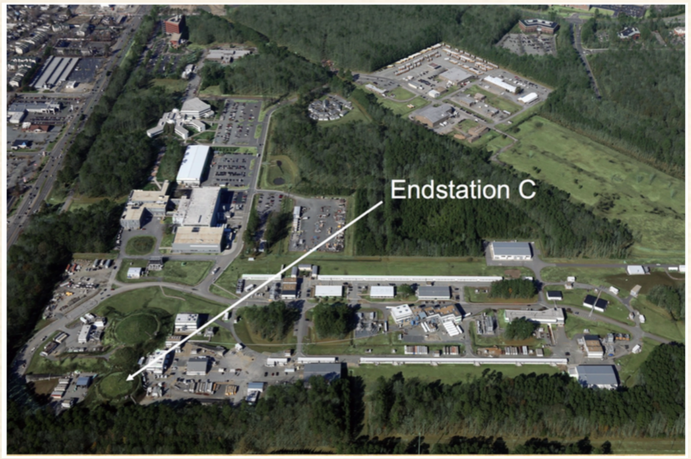
A_{PV} in elastic e-p scattering: Qweak at JLab

The Weak Charge of the Proton



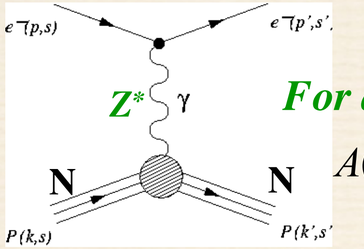
For a ^1H target, nucleon structure contribution well-constrained from measurements

$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[\, Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right] \qquad Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$



A_{PV} in elastic e-p scattering: Qweak at JLab

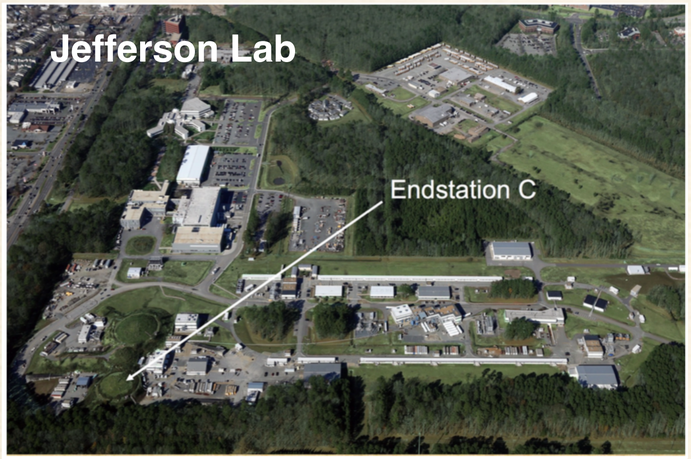
The Weak Charge of the Proton

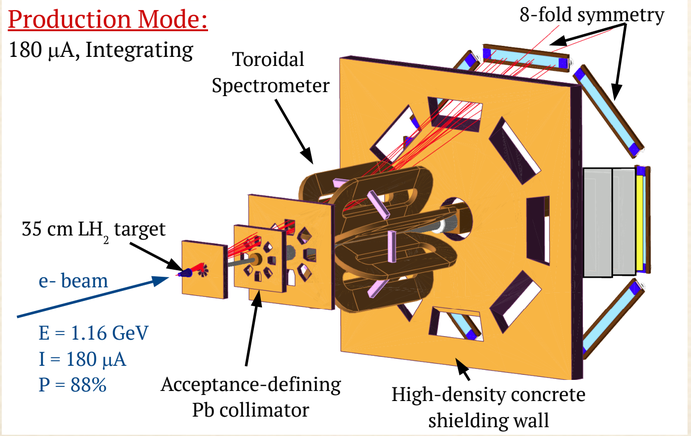


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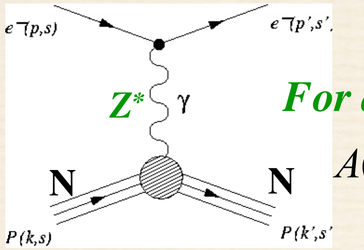
Two Production Runs: Feb-May '11, Nov '11-May '12





A_{PV} in elastic e-p scattering: Qweak at JLab

The Weak Charge of the Proton

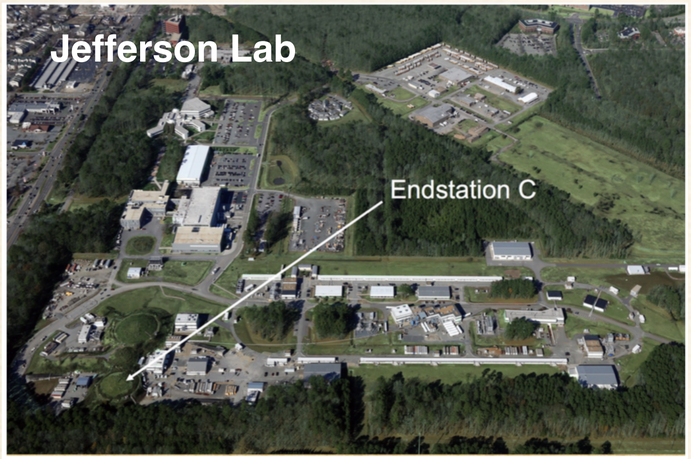


Final result published: Nature 557 (2018) no.7704, 207-211

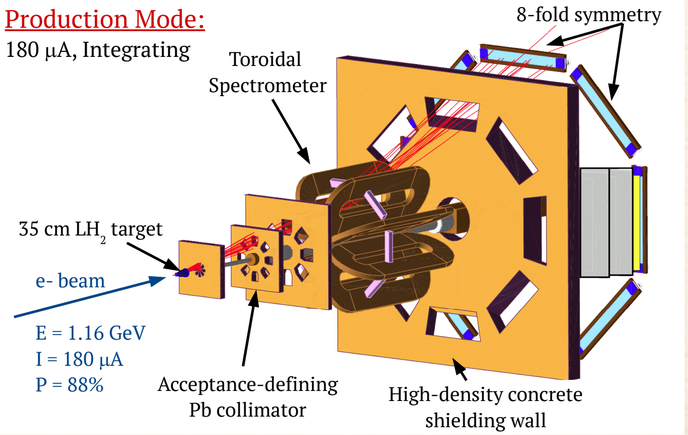
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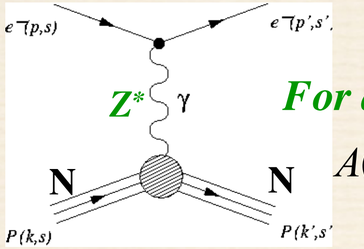


Production Mode:
180 μA, Integrating



A_{PV} in elastic e-p scattering: Qweak at JLab

The Weak Charge of the Proton

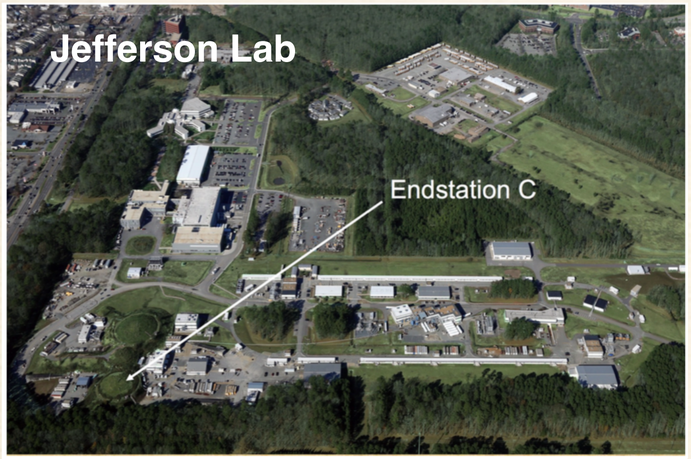


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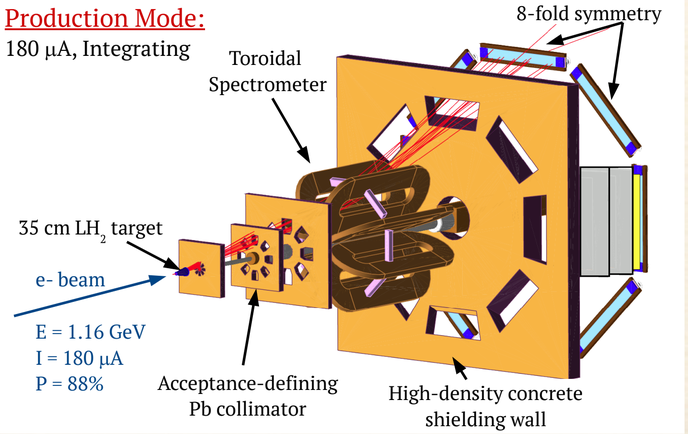
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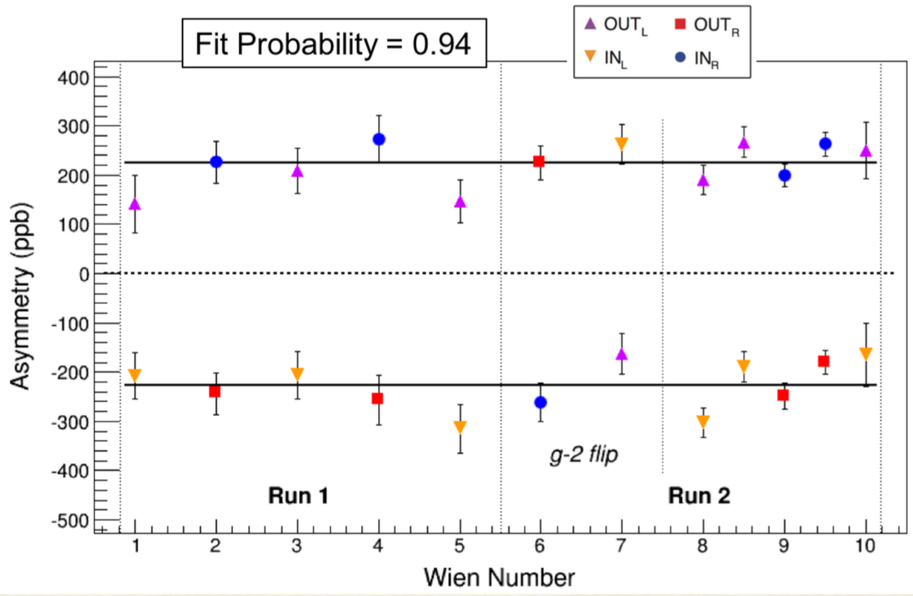
Two Production Runs: Feb-May '11, Nov '11-May '12



Production Mode:
180 μA, Integrating



Behavior of Asymmetry under Slow Reversals



Three slow reversal types:

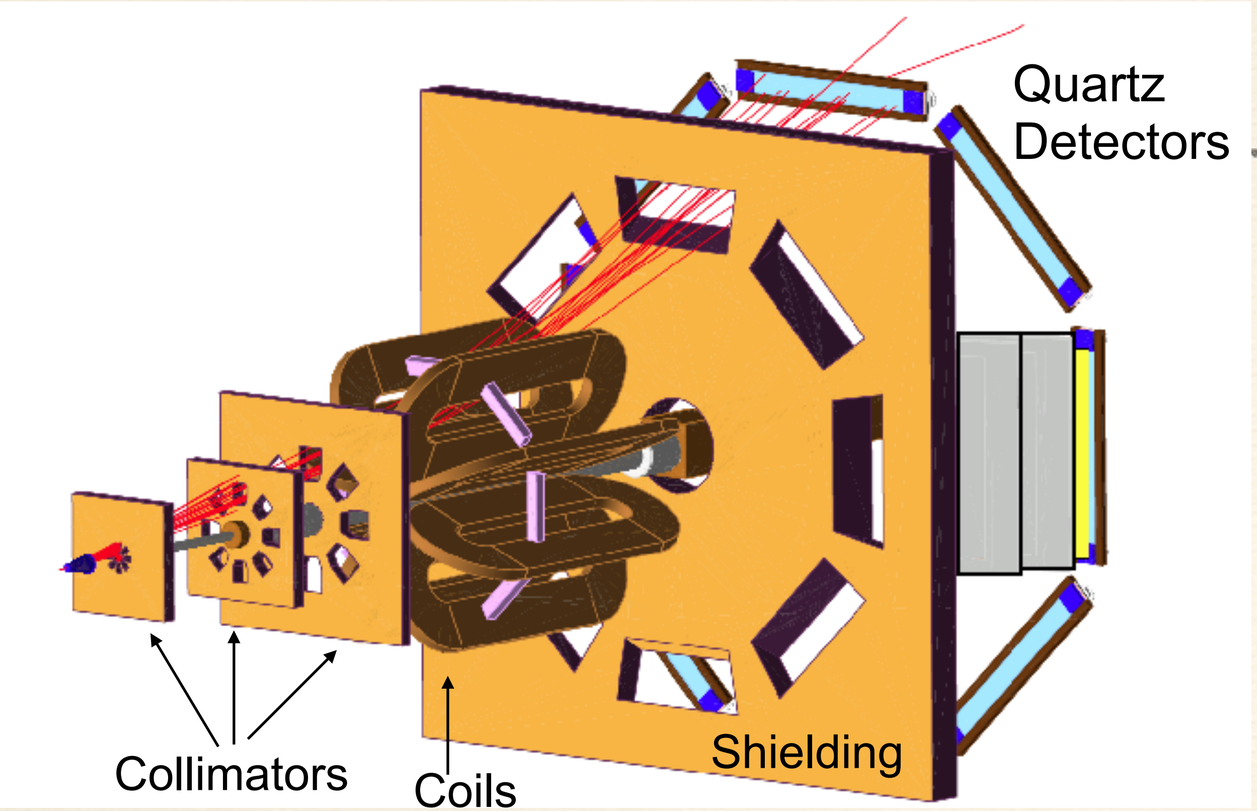
IN/OUT: reversal of laser helicity (IWHP)

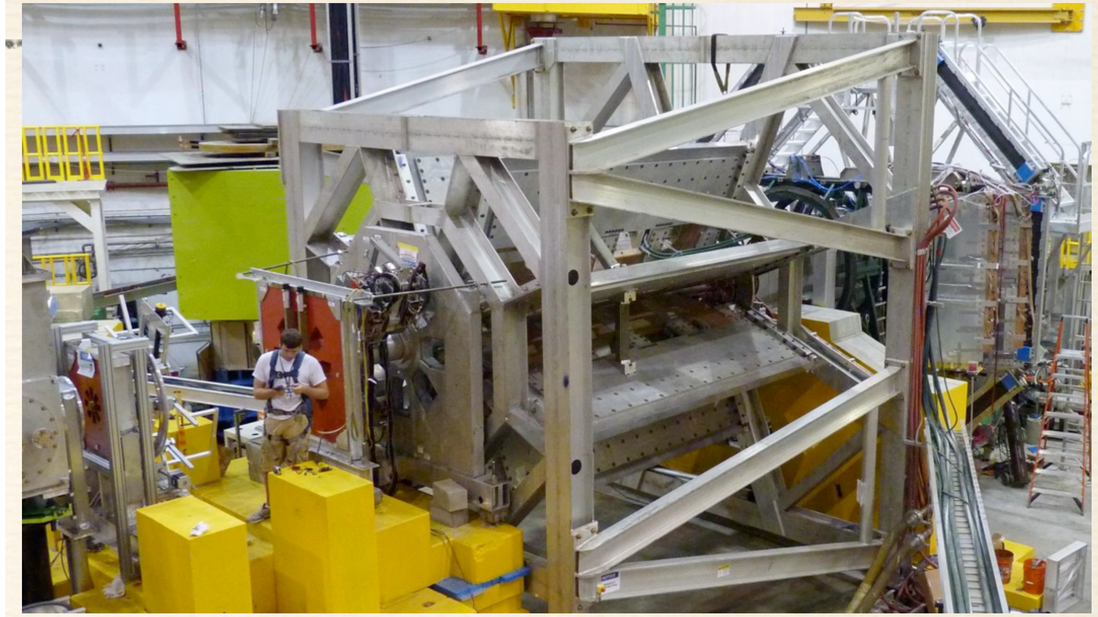
L/R: reversal of electron beam via Wien filter

g-2 flip: reversal of electron via spin precession in accelerator

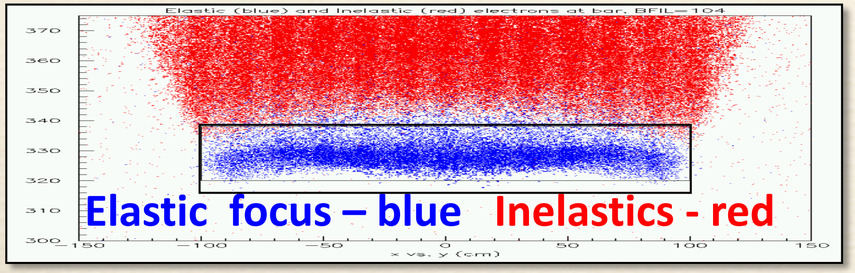
Combining the data without sign corrections gives
NULL average = -1.75 ± 6.51 ppb
- consistent with zero, as expected

Qweak Spectrometer



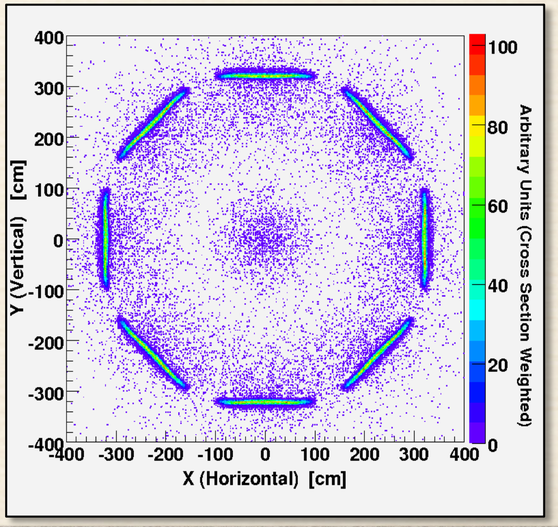


Toroidal Spectrometer separates elastics into each of 8 detectors



Each detector:

- 2 meters long
- lead radiator, fused silica
- Cerenkov light from shower
- collected by phototube at each end

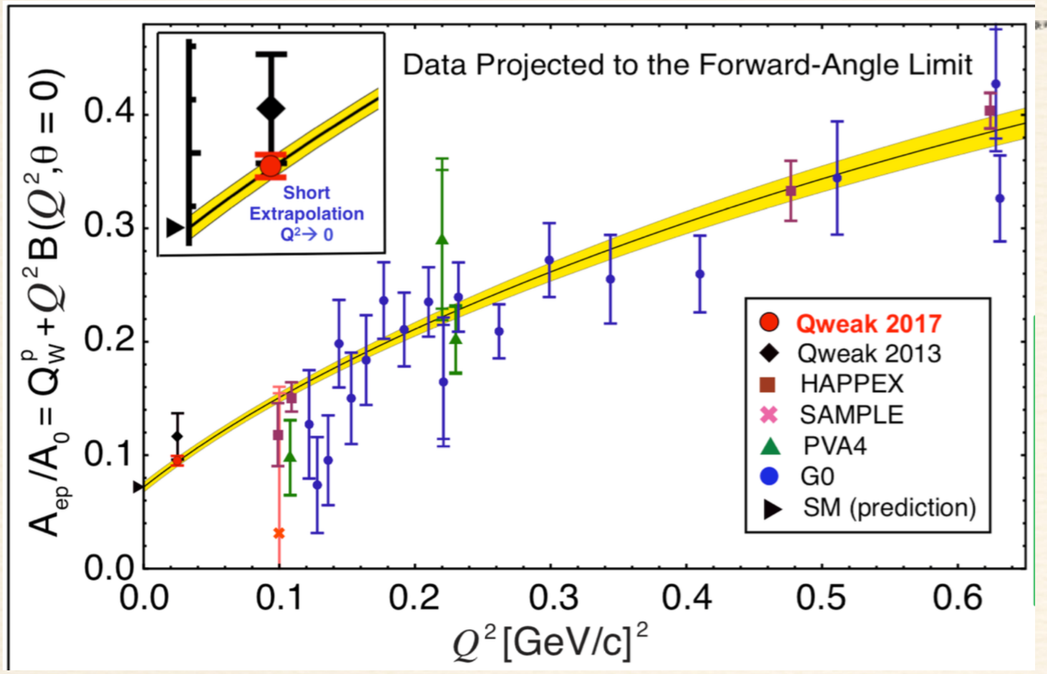


$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst}) \text{ ppb at } \langle Q^2 \rangle = 0.0249 \text{ (GeV/}c)^2$$

QWeak Result

Nature 557 (2018) no.7704, 207-211

SM: 0.0708 ± 0.0003



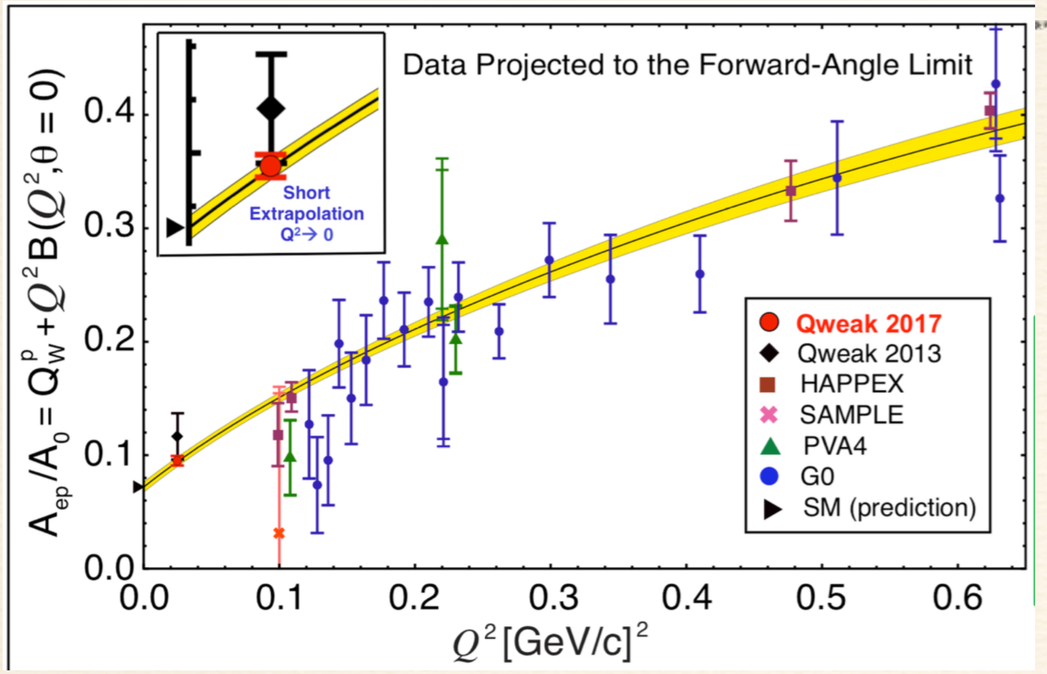
Quantity	Value	Error
Q_W^p	0.0719	0.0045
$\sin^2\theta_W$	0.2382	0.0011
ρ_s	0.19	0.11
μ_s	-0.18	0.15
$G_A^{Z(T=1)}$	-0.67	0.33

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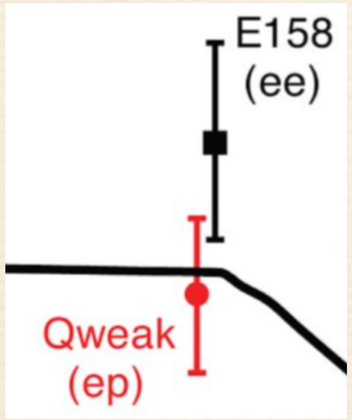
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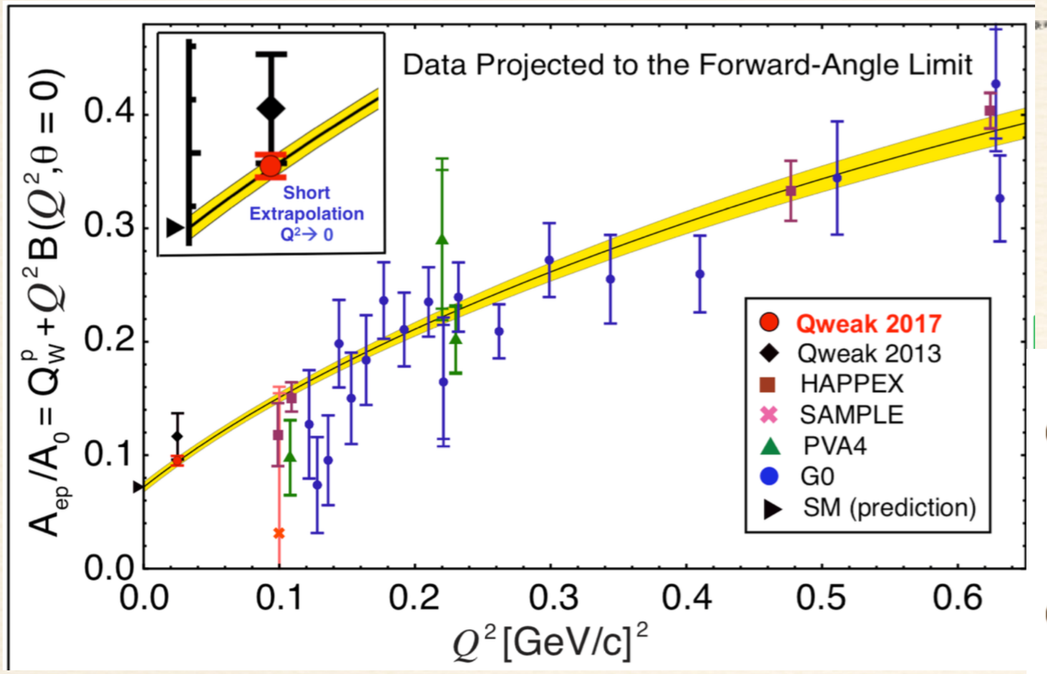


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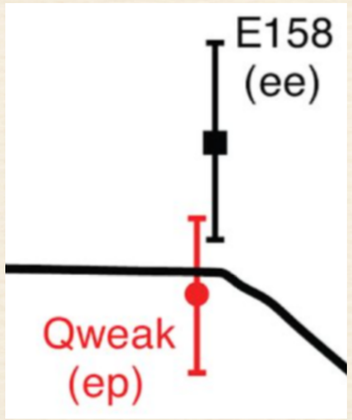
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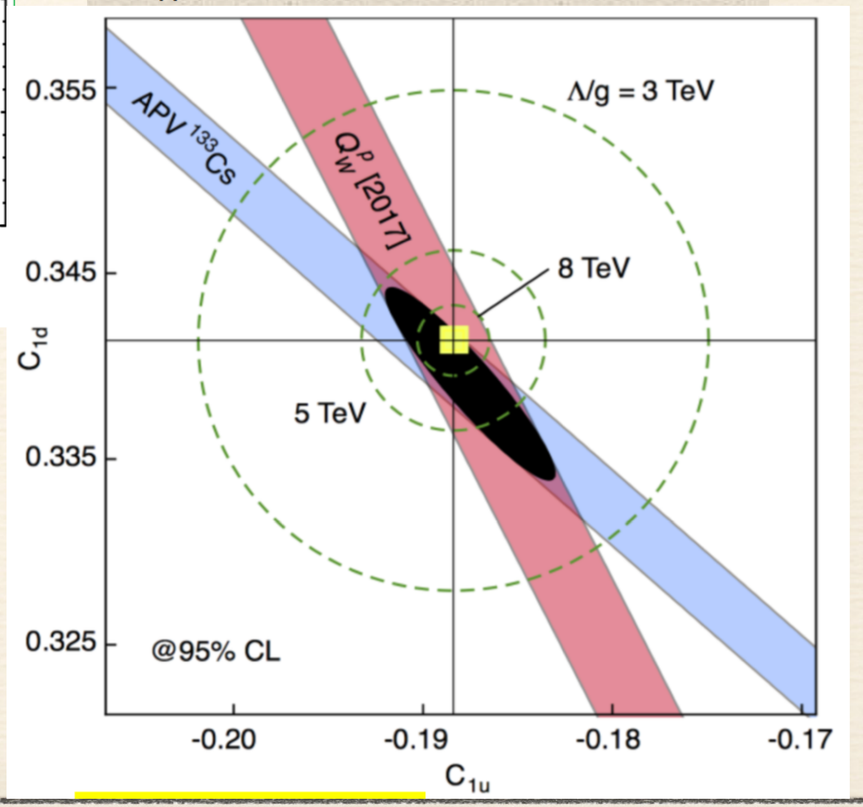
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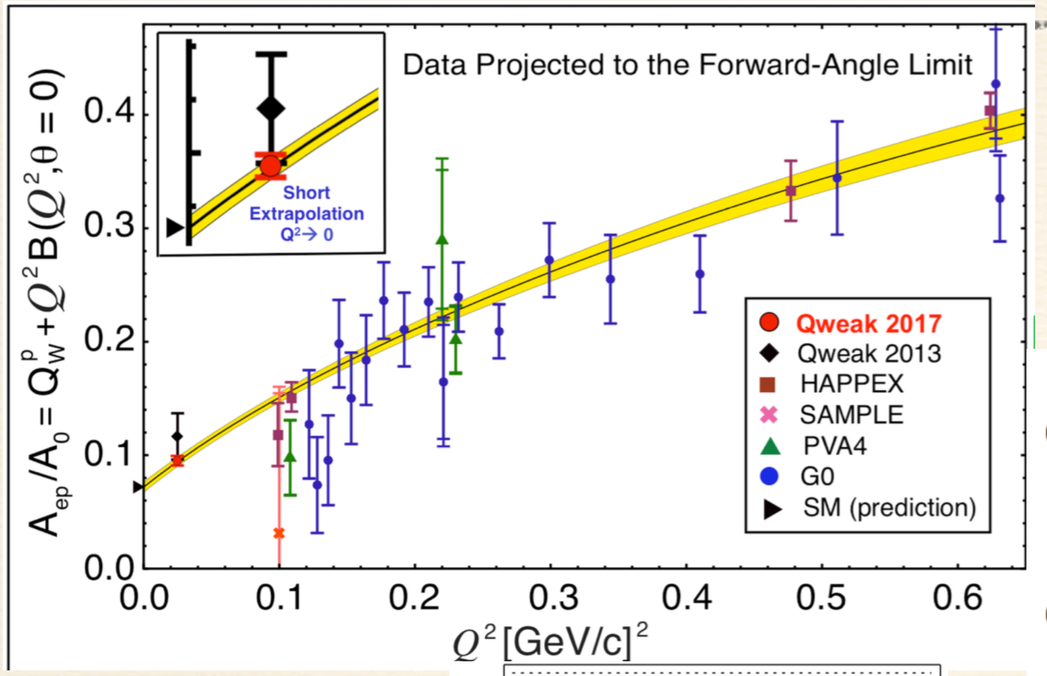


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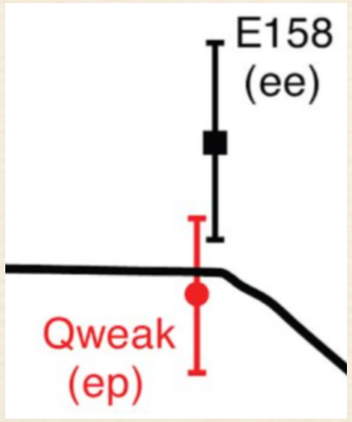
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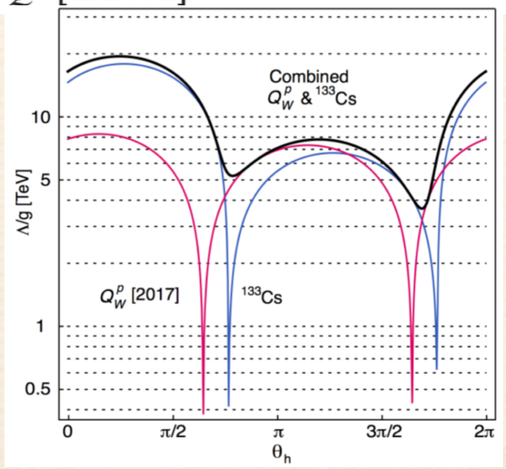
Nature 557 (2018) no.7704, 207-211

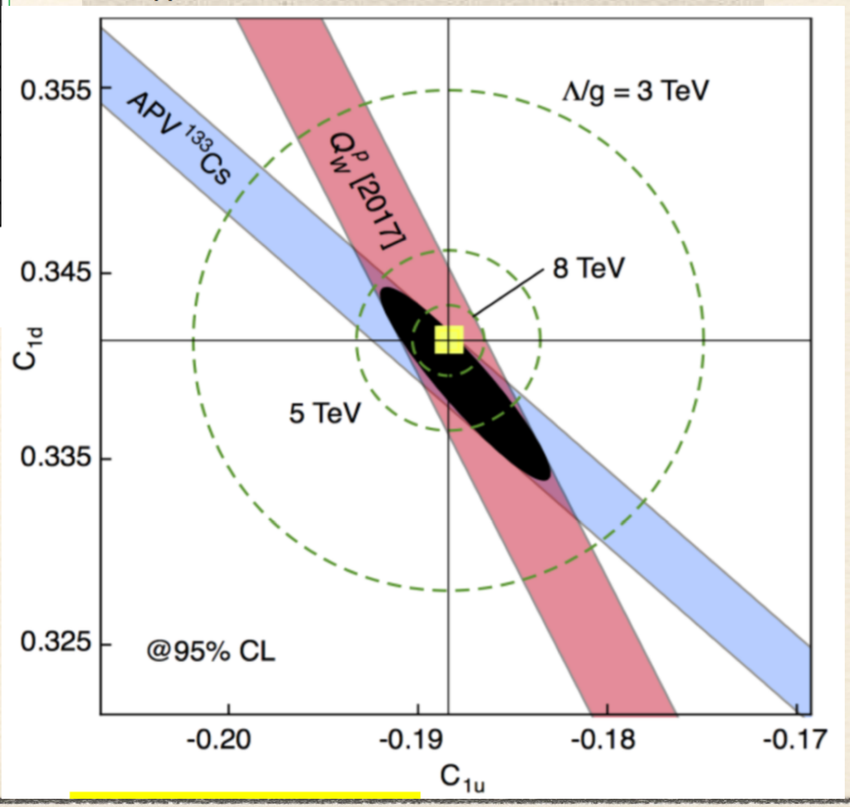
SM: 0.0708 ± 0.0003



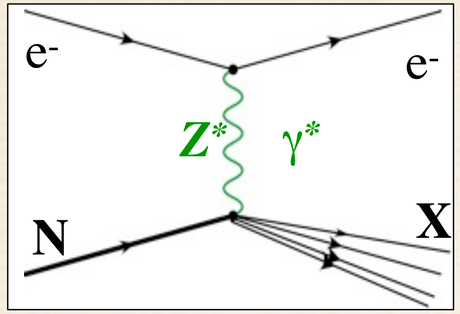
Quantity	Value	Error
Q_W^p	0.0719	0.0045
$\sin^2\theta_W$	0.2382	0.0011
ρ_s	0.19	0.11
μ_s	-0.18	0.15
$G_A^{Z(T=1)}$	-0.67	0.33







PVDIS in Hall A



A_{PV} in deep inelastic e-D scattering:

$Q^2 >> 1$ GeV^2 , $W^2 >> 4$ GeV^2

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)\,b(x)\right]$$

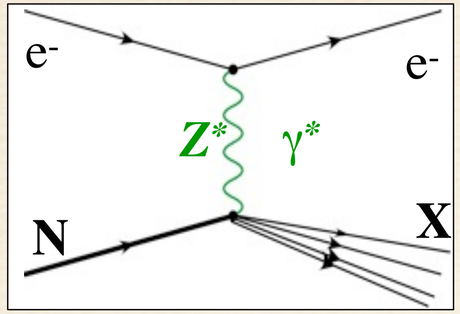
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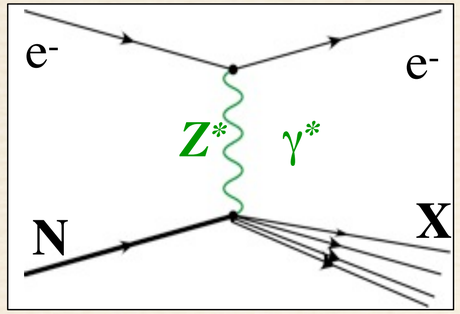
6 GeV run results

Q^2 ~ 1.1 GeV^2

A^{phys} (ppm)	−91.10
(stat.)	±3.11
(syst.)	±2.97
(total)	±4.30

Q^2 ~ 1.9 GeV^2	Asymmetry
A^{phys} (ppm)	−160.80
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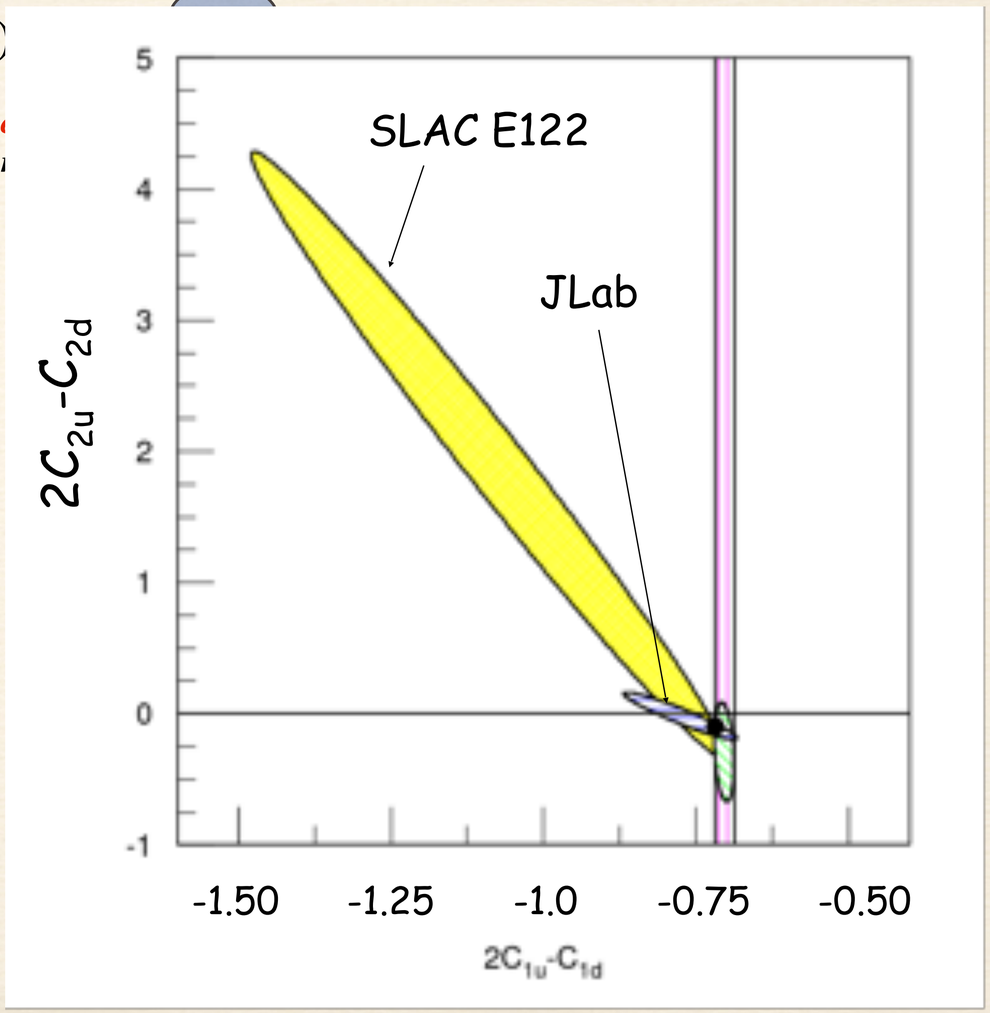
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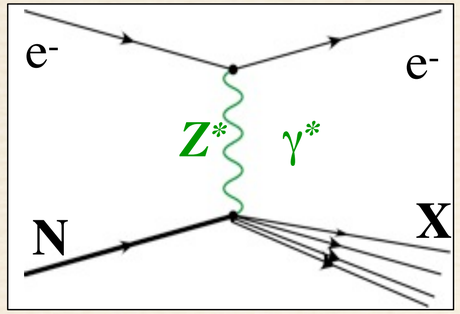
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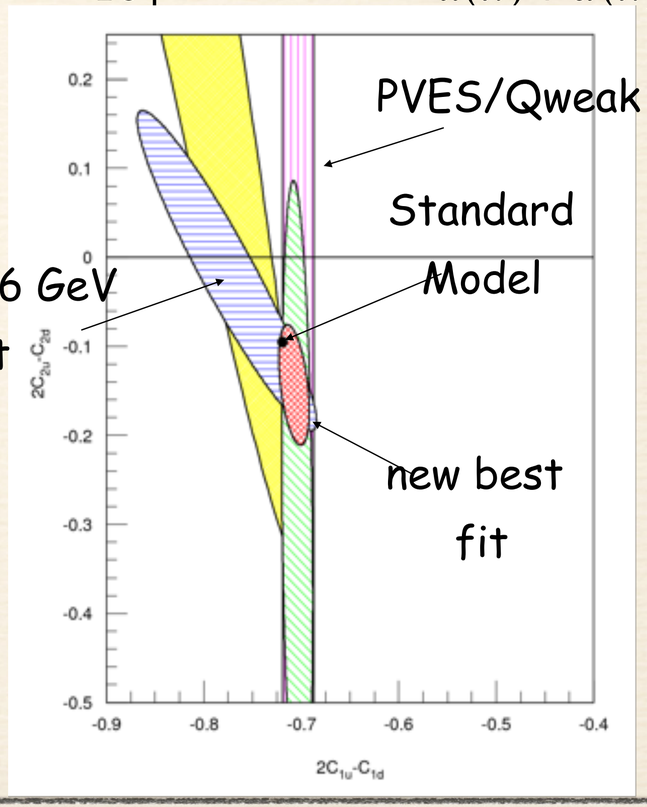
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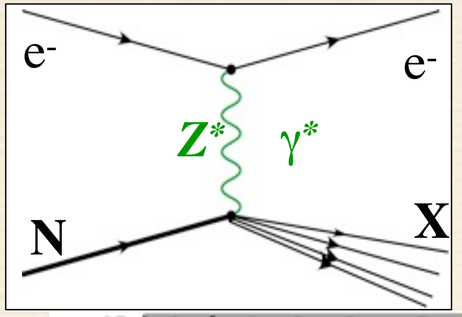
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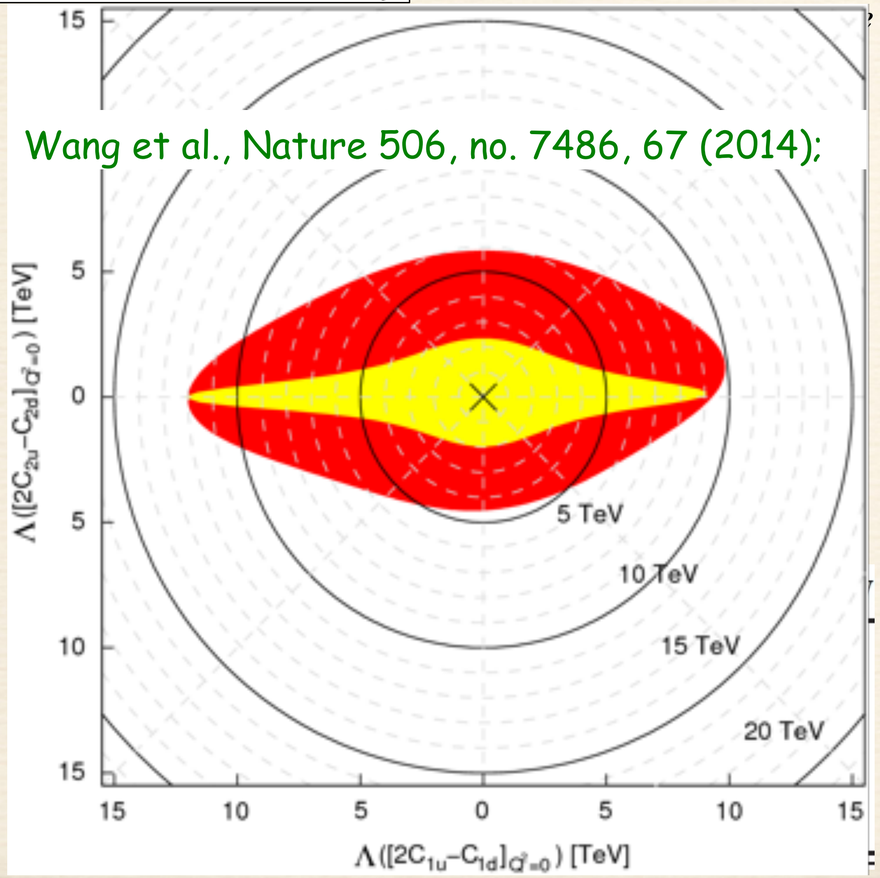
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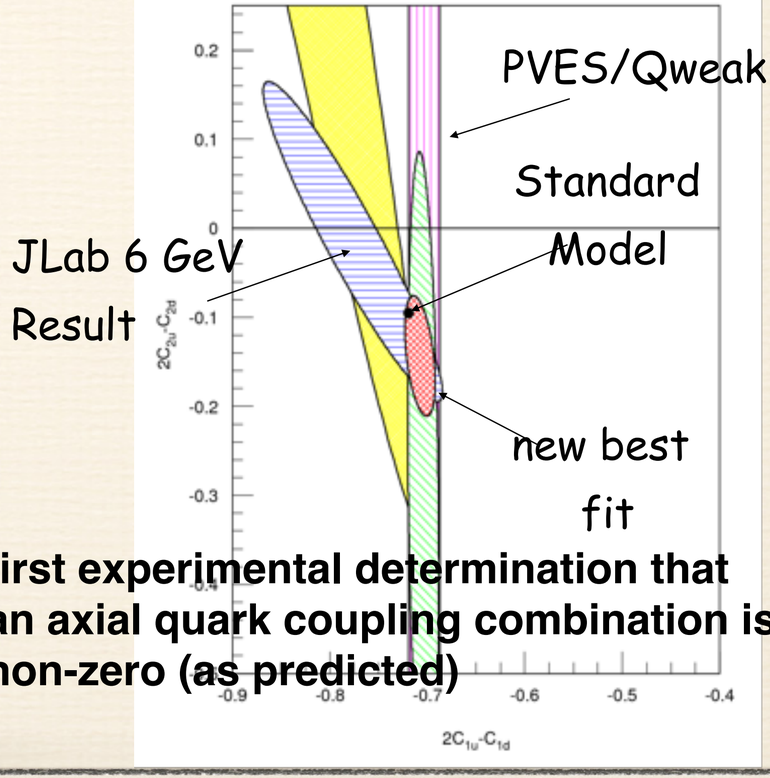
PARTICLE PHYSICS

Quarks are not ambidextrous

W. Marciano
article in Nature

By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. SEE LETTER P.67



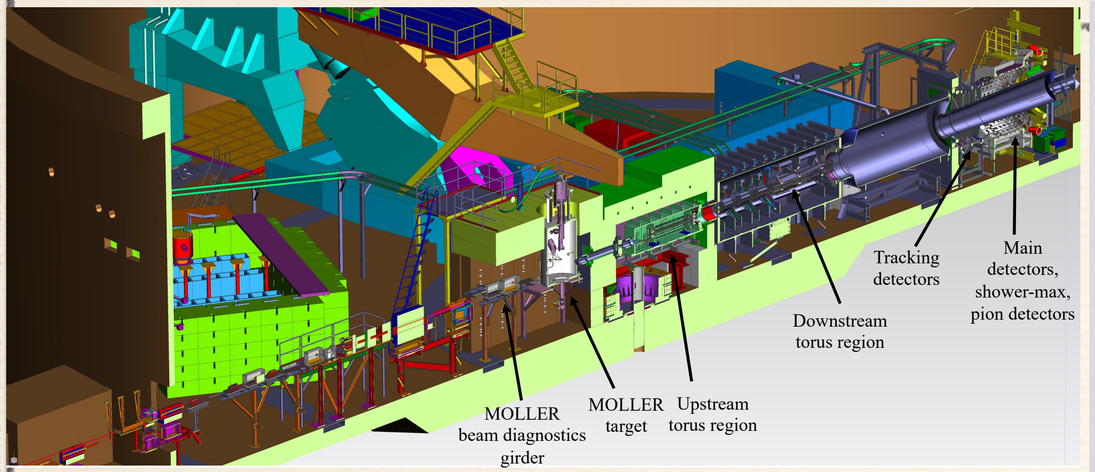


first experimental determination that an axial quark coupling combination is non-zero (as predicted)

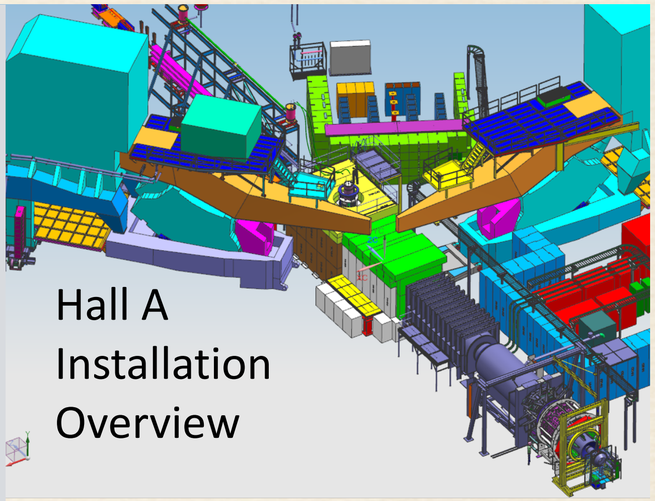
The Future

MOLLER Experiment

Engineering Design and major acquisitions complete and construction has begun

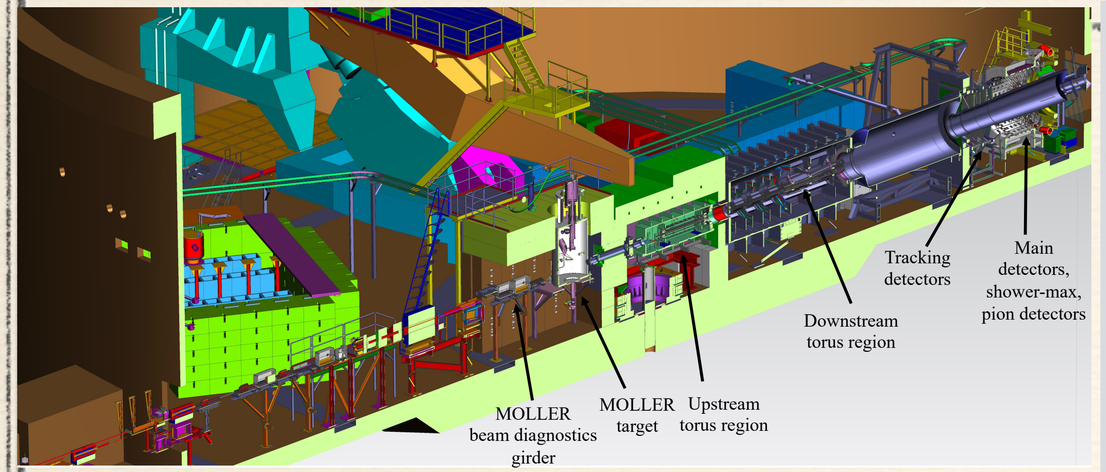


- **~ 50M$ MIE by US DOE NP**
- **~ 12M$: US NSF and Canada CFI/Research Manitoba**
- **CD-1 granted in Dec 2020**
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- **Construction: 2024-25**
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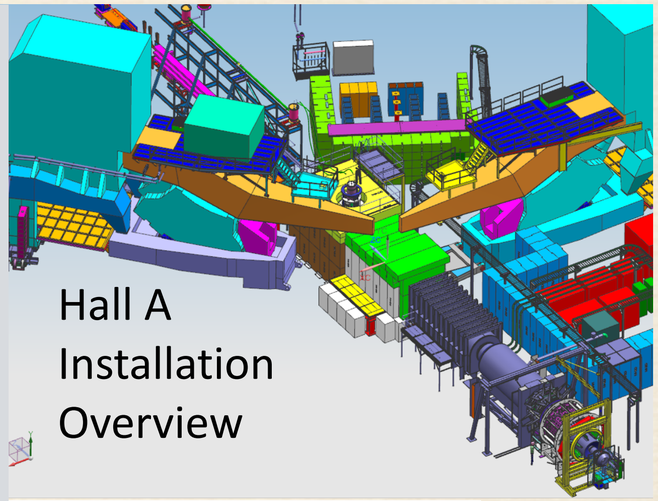


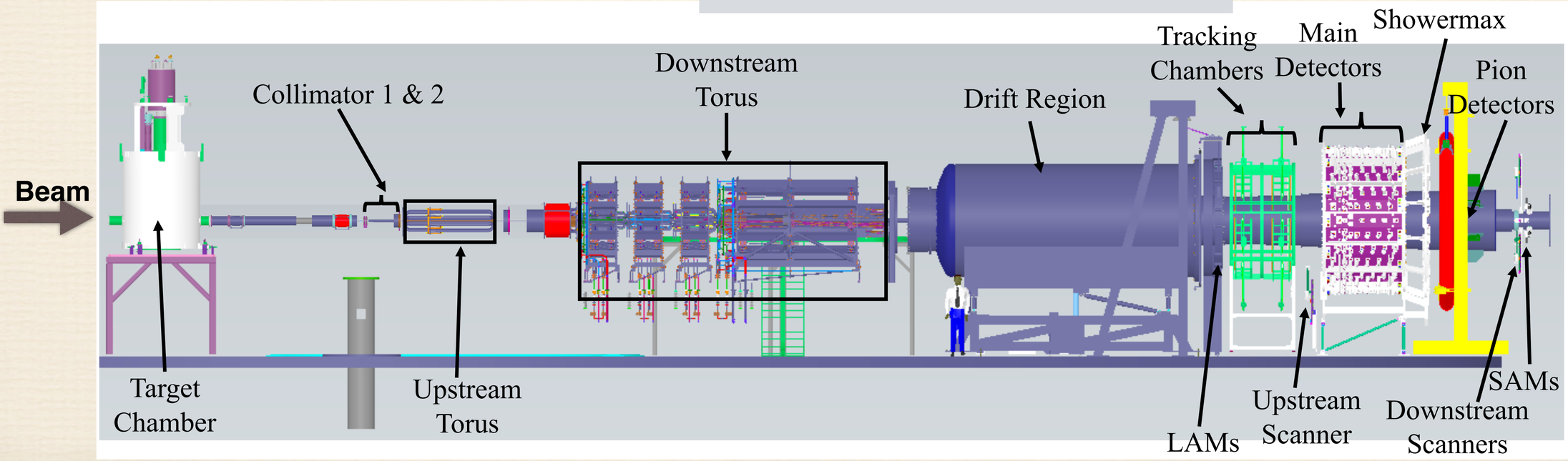
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The MOLLER Sensitivity

A new experiment to measure parity-violating Møller scattering at Jefferson Lab

11 GeV, 65 μA 90% beam polarization

$A_{PV} \sim 32$ ppb $\delta(A_{PV}) \sim 0.8$ ppb

$\delta(Q^e_W) = \pm 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$

$\delta(\sin^2\theta_W) = \pm 0.00023\ (stat.) \pm 0.00012\ (syst.)$

$\Rightarrow \sim 0.1\%$

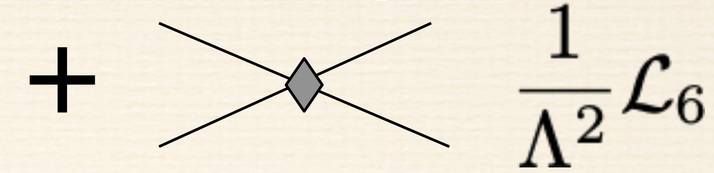
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$$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6$$

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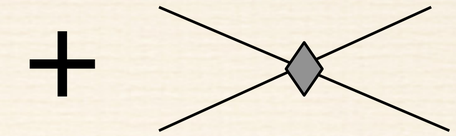
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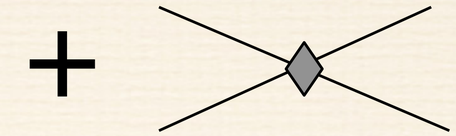
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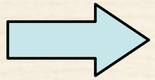
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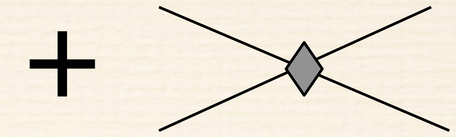
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MOLLER Reach

$\Lambda^{ee}_{LL} \sim 27$ TeV

$\Lambda^{ee}_{RR-LL} \sim 38$ TeV

LEP-200 insensitive

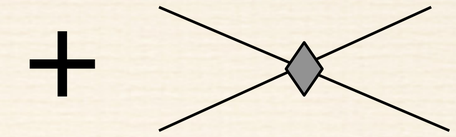
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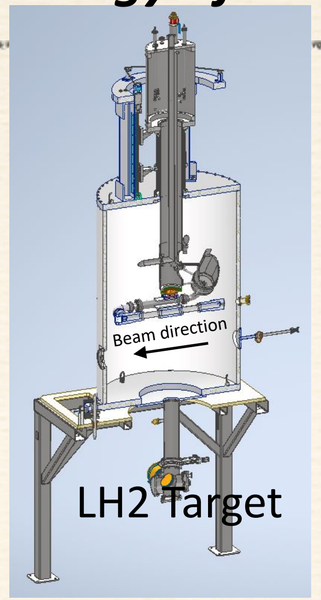
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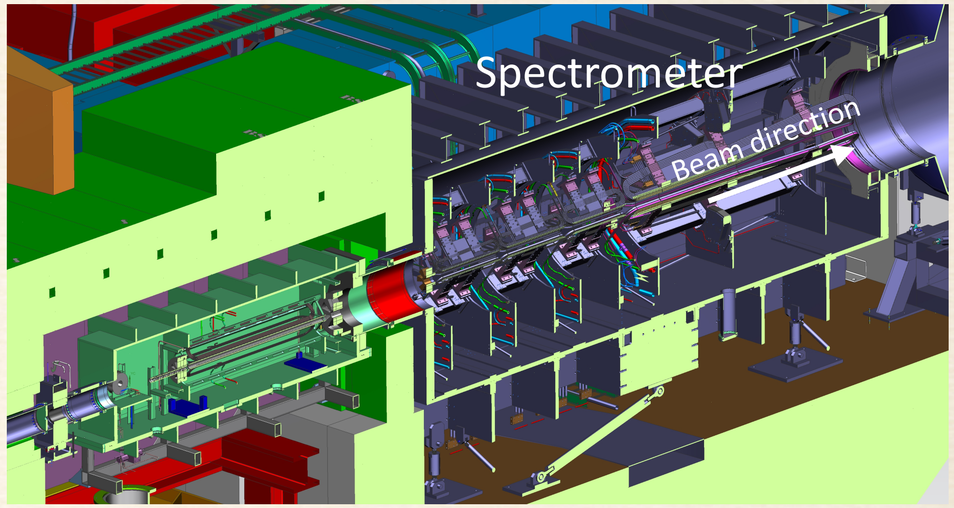
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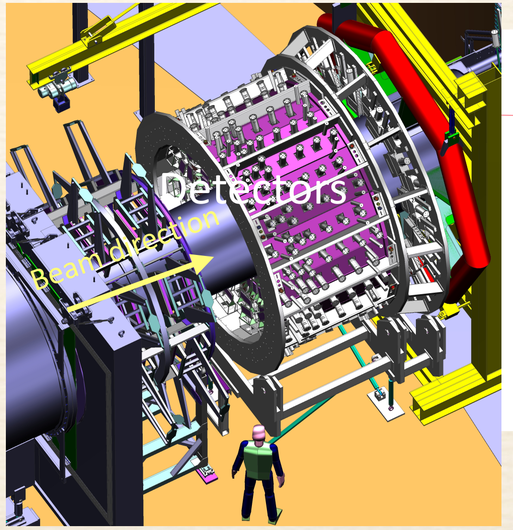
MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

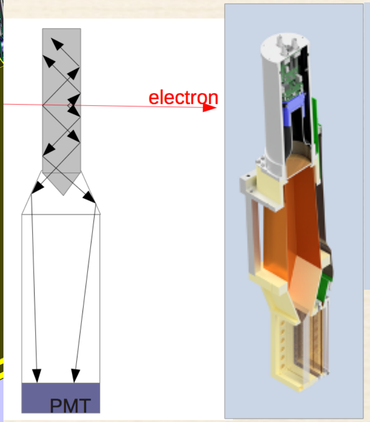
MOLLER Technical

Evolutionary Improvements from Technology of Third Generation Experiments

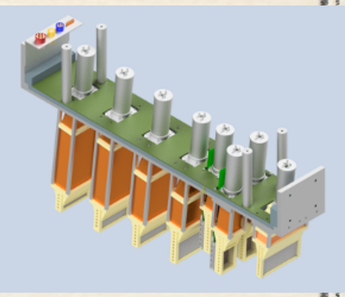








Single channel

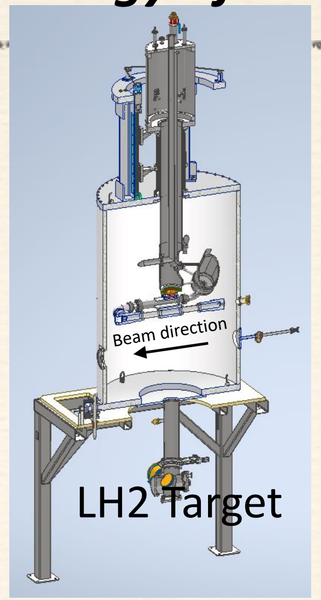


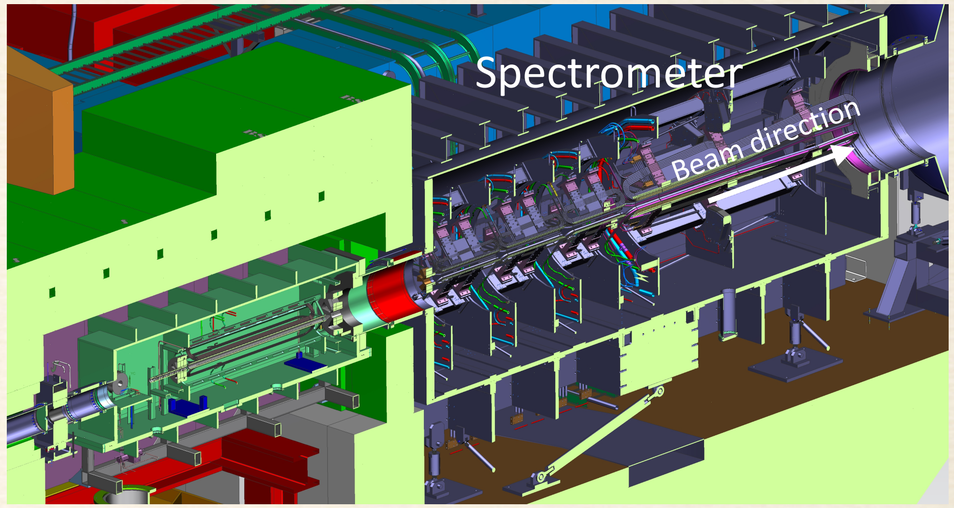
1/28th Segment

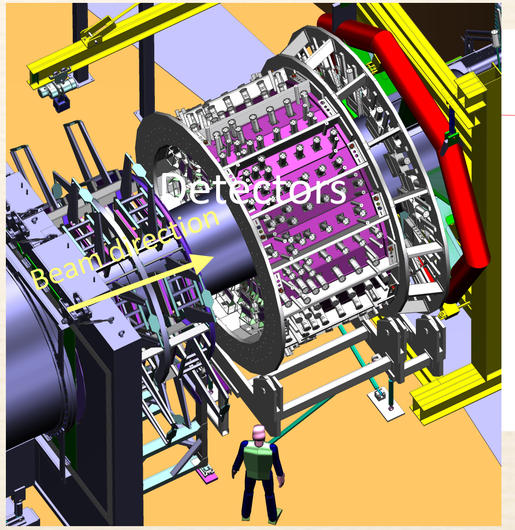
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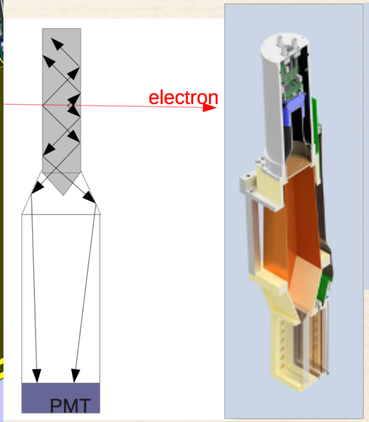
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- **High intensity polarized electron source**

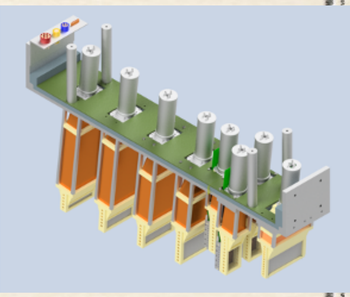








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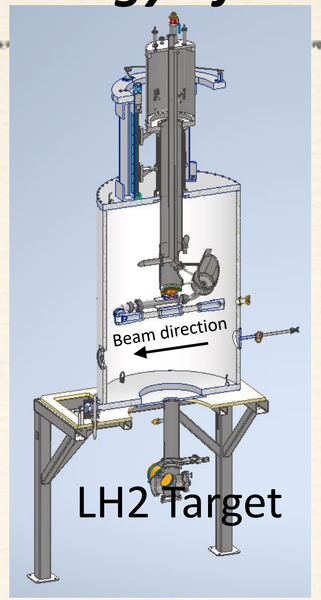


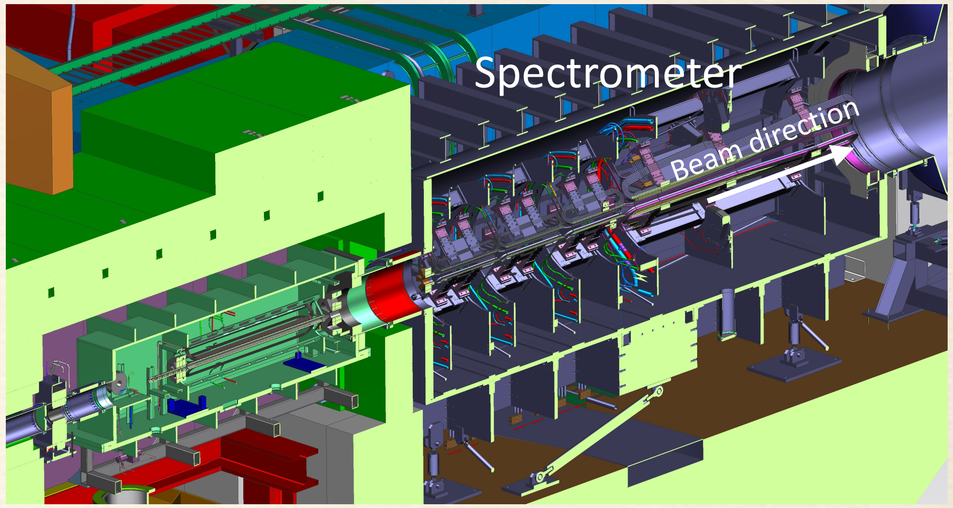
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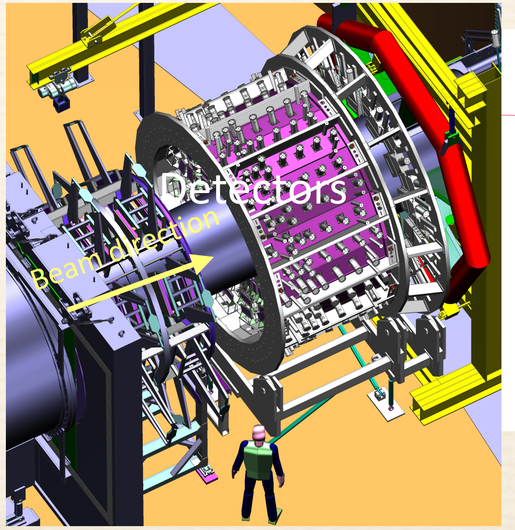
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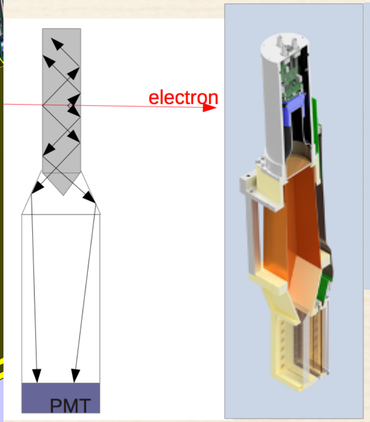
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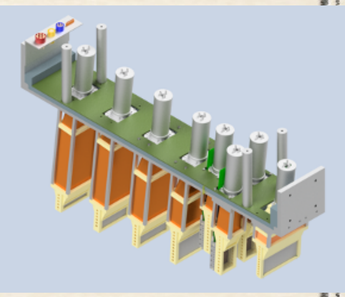








Single channel

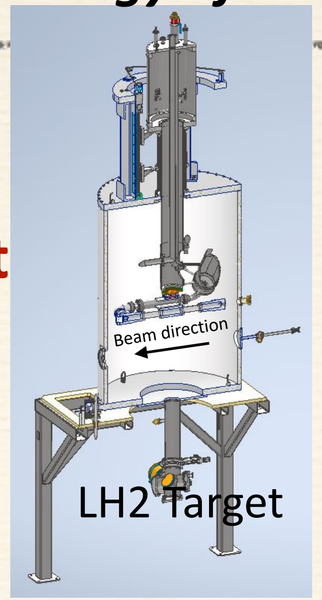


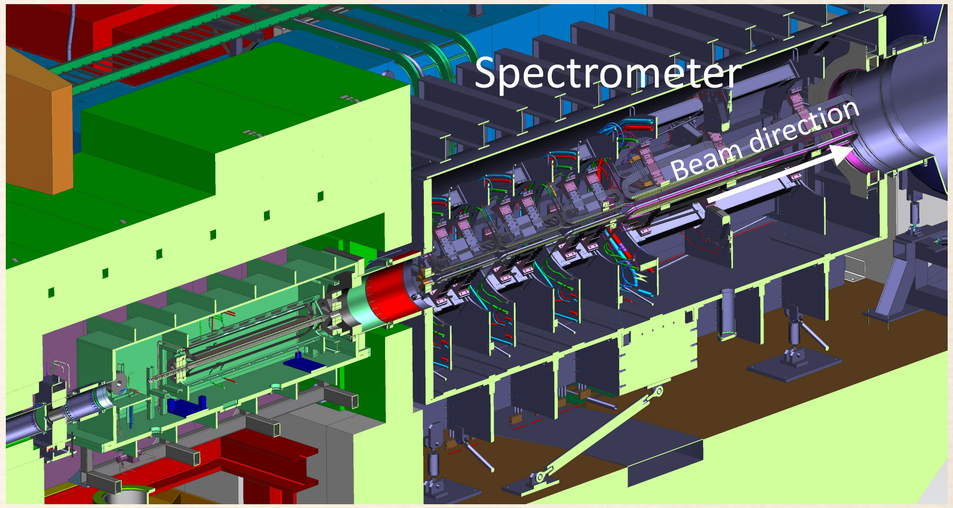
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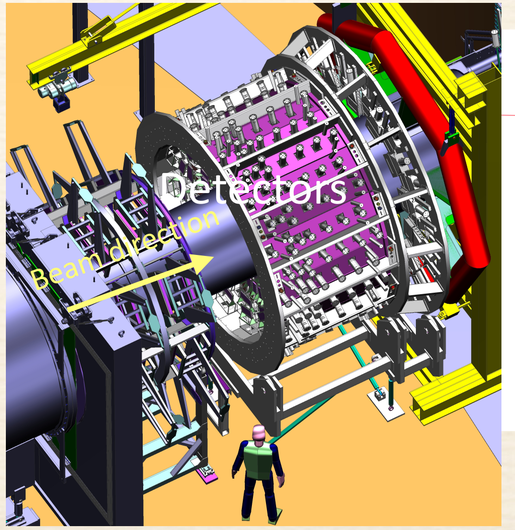
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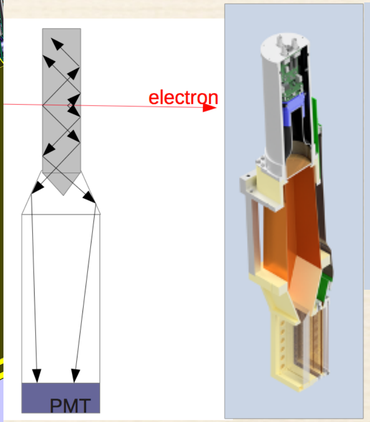
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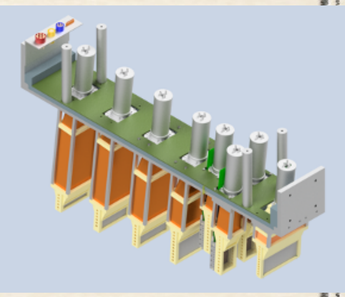








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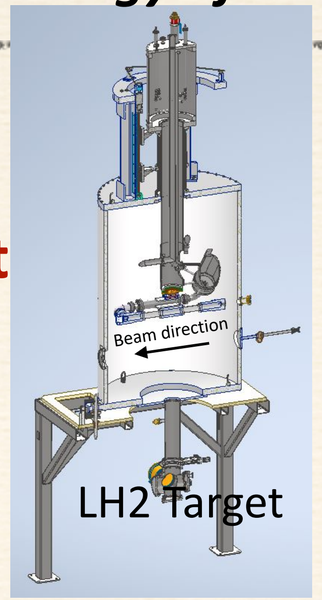


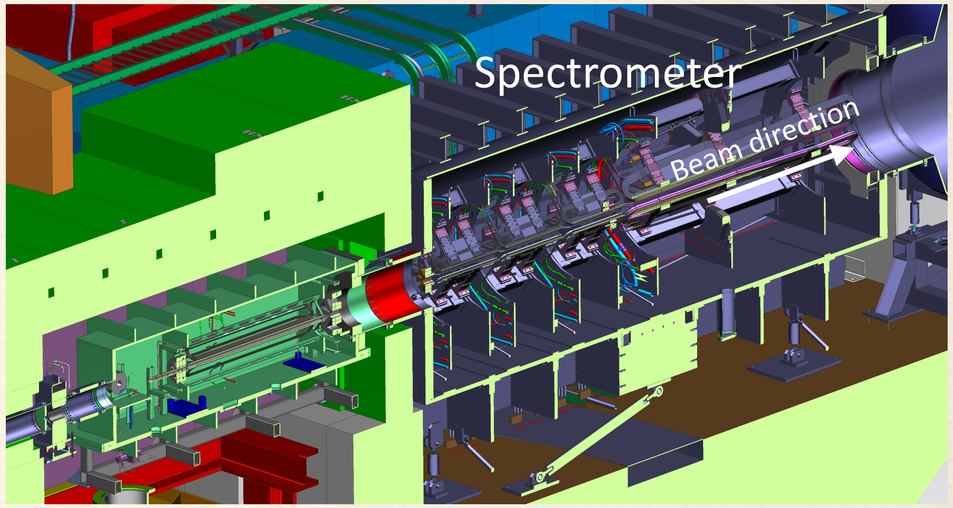
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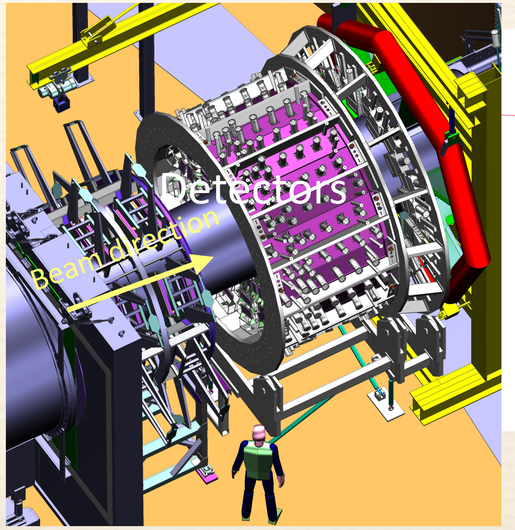
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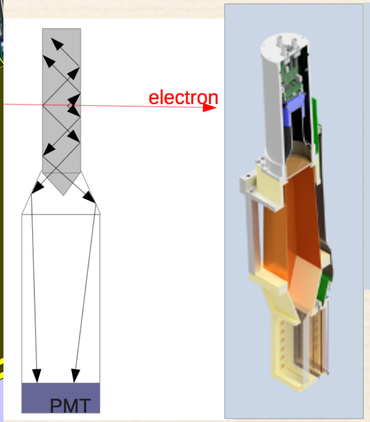
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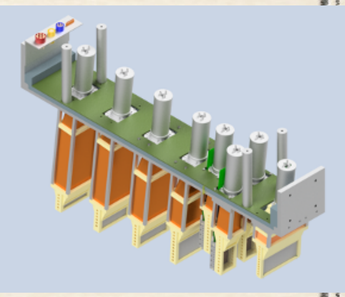








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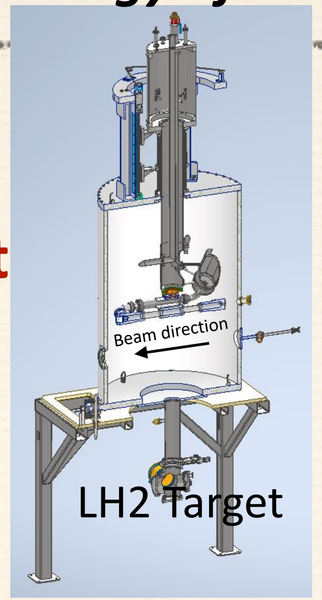


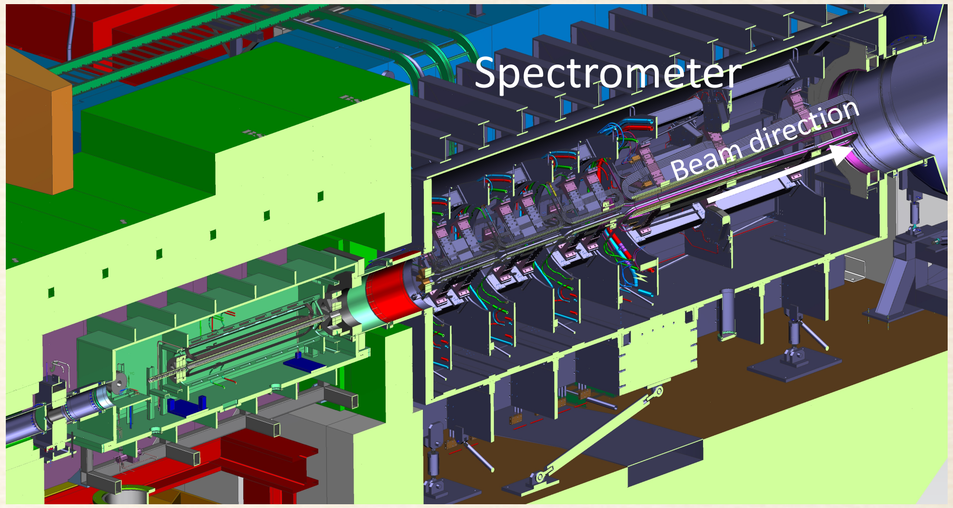
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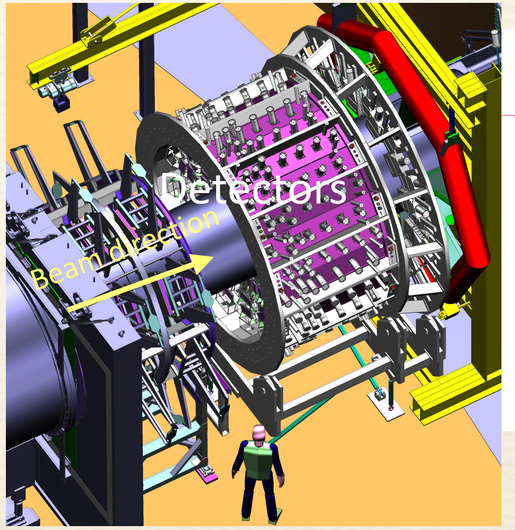
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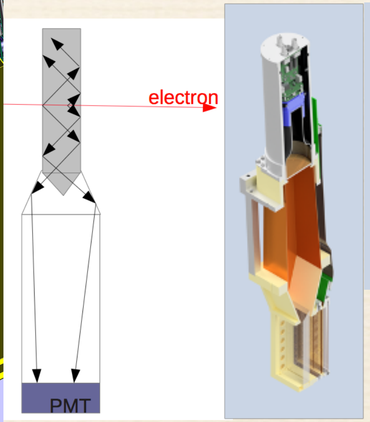
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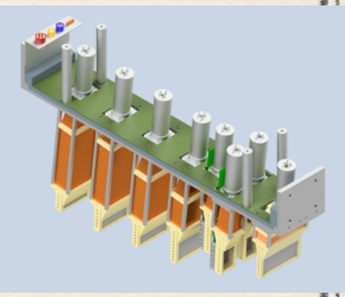








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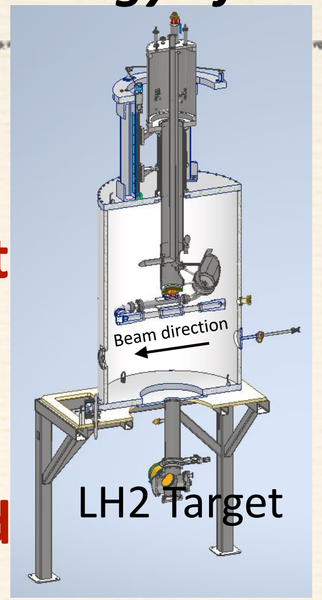


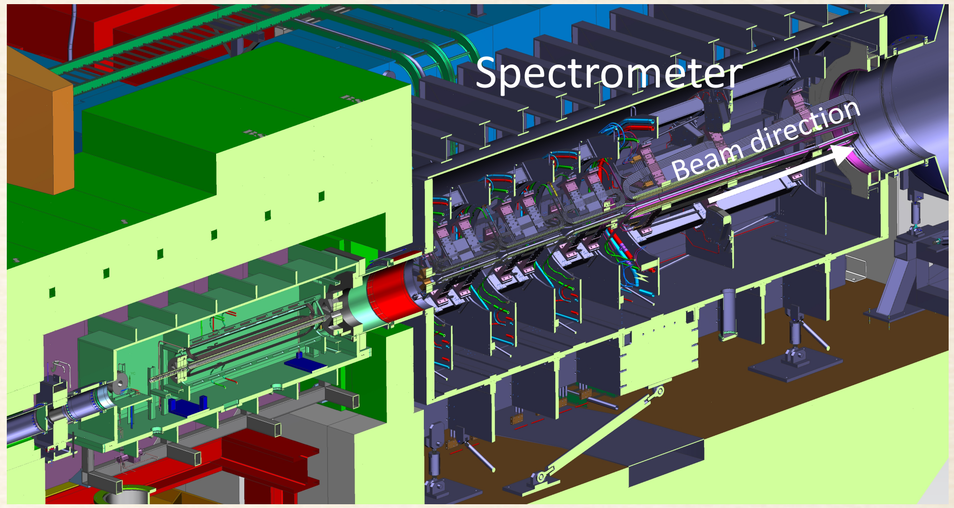
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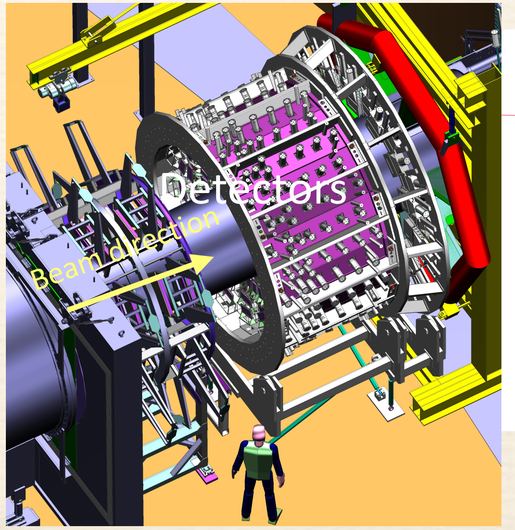
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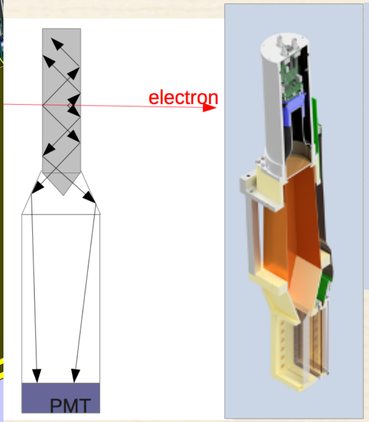
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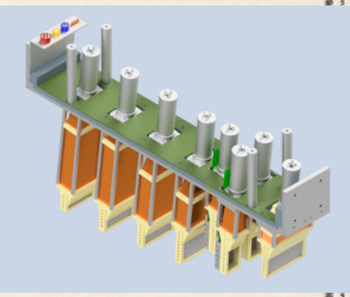








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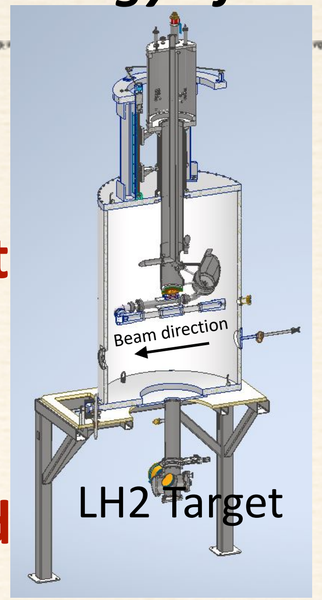


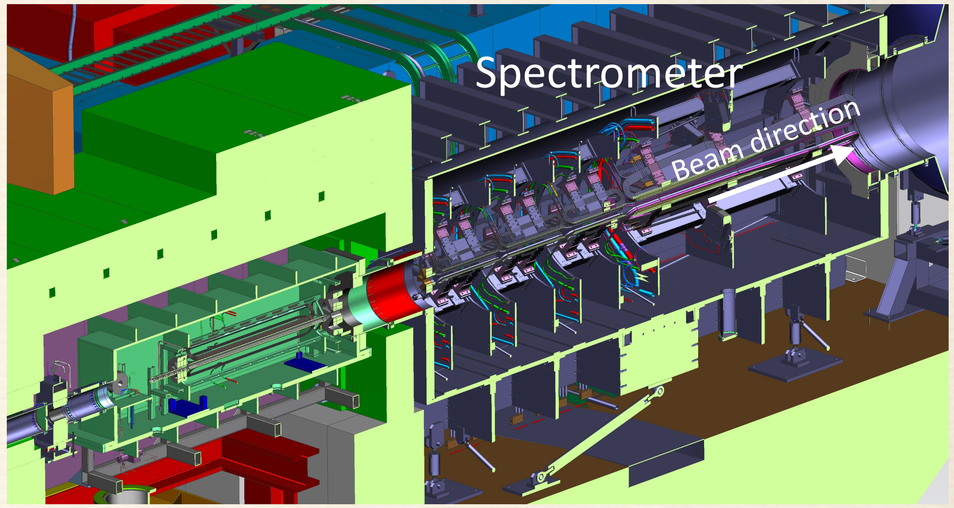
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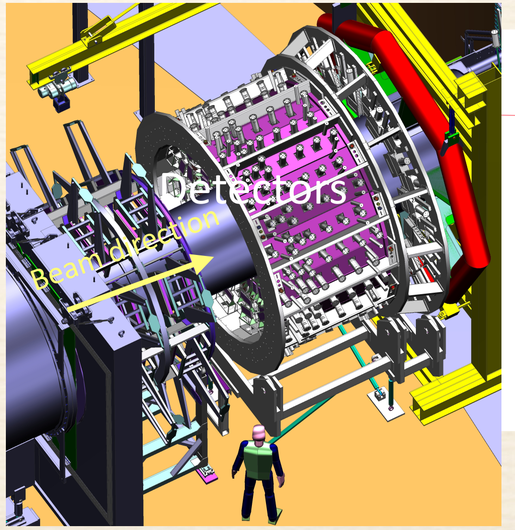
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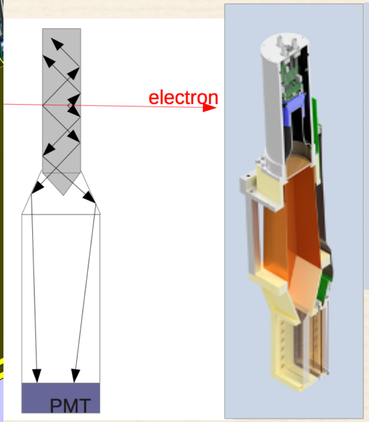
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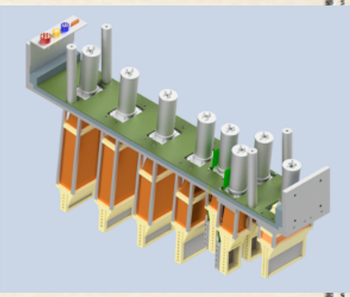








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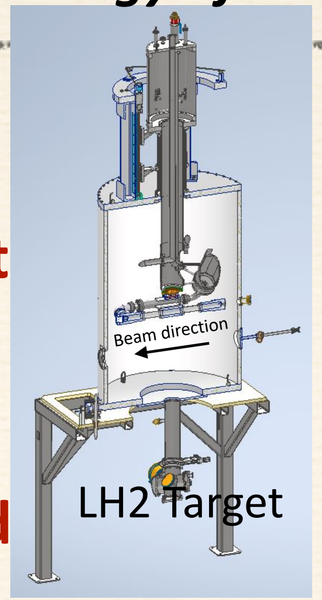


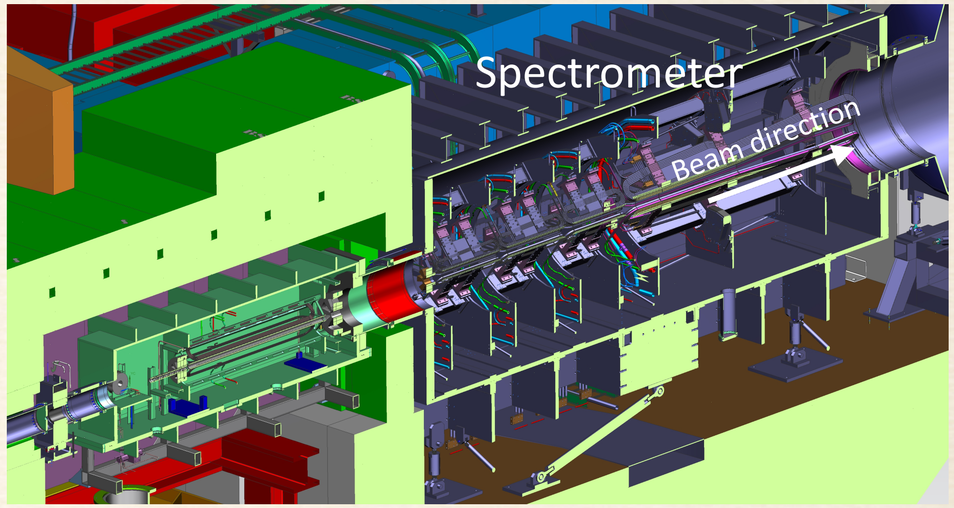
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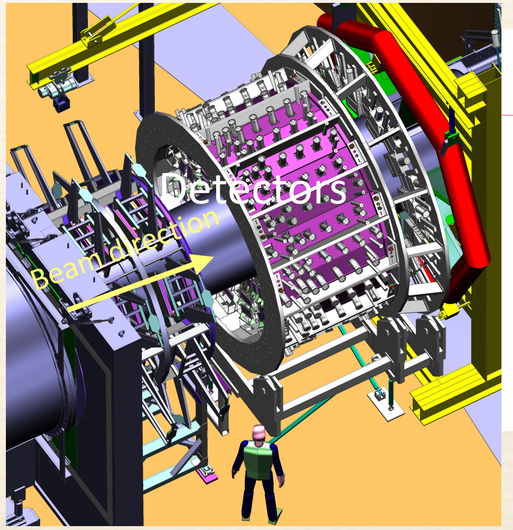
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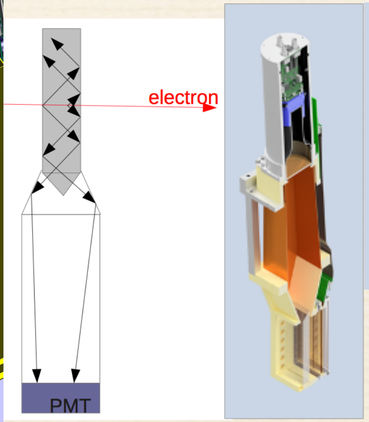
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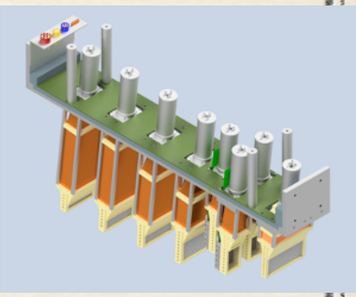








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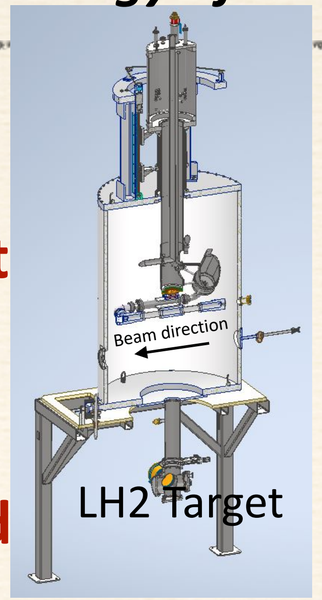


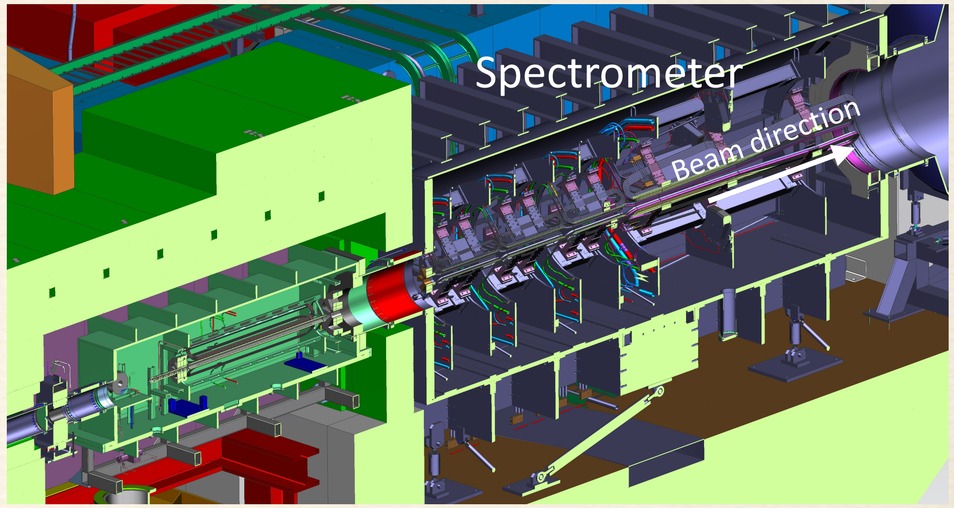
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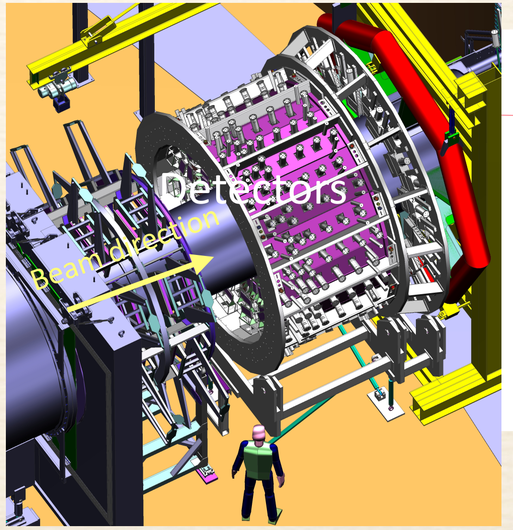
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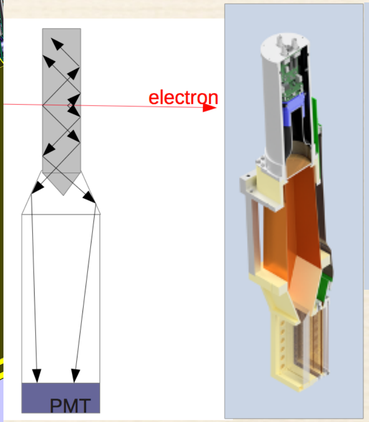
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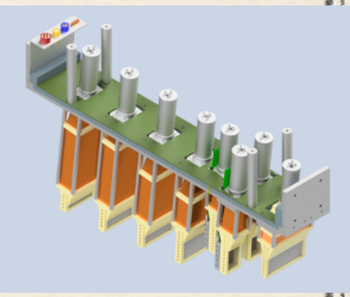








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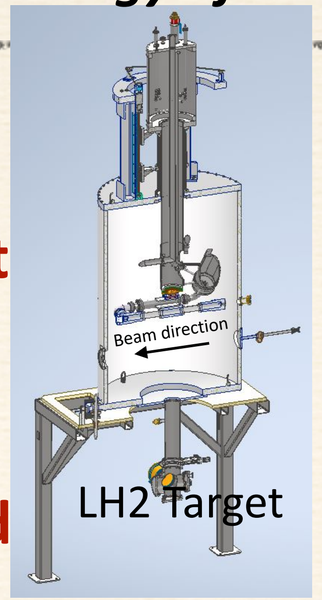


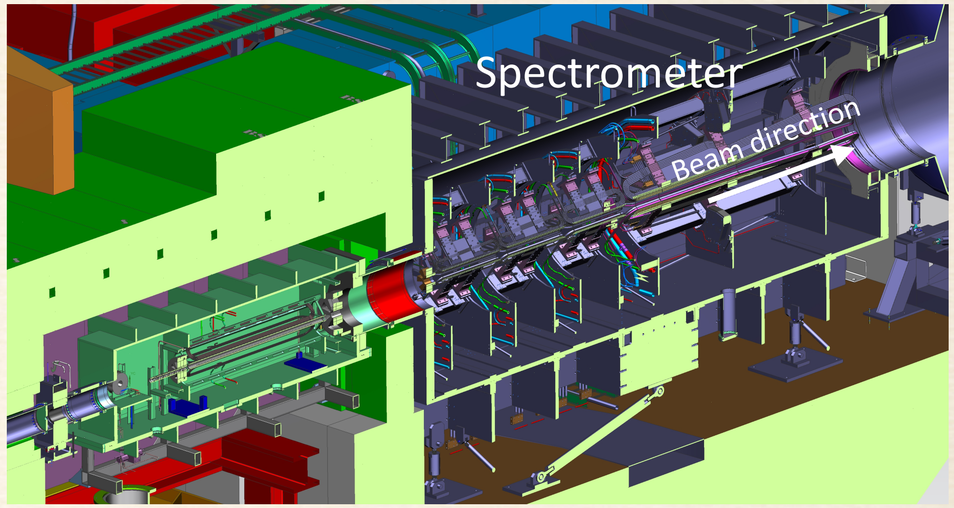
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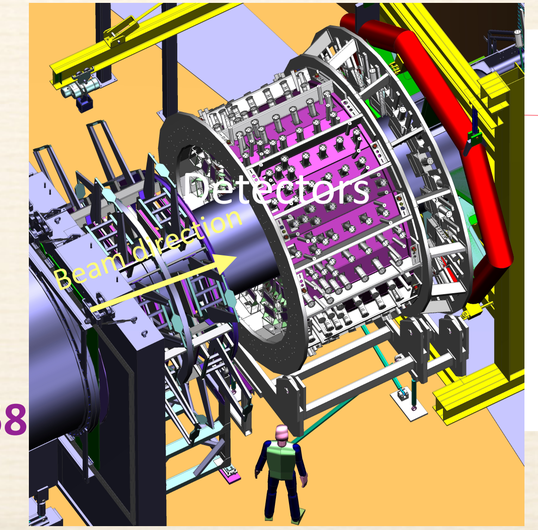
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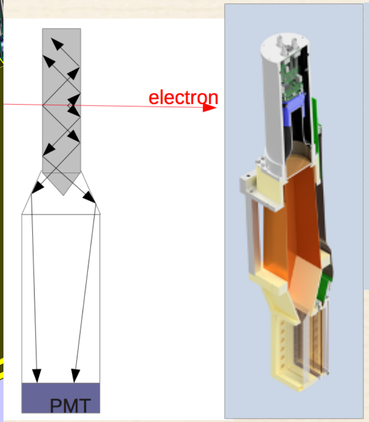
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- **MOLLER Collaboration Team**
  - **~ 180 scientists from more than 30 institutions (3 countries)**
  - **Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158**
  - **Final Technical Design Report is public**

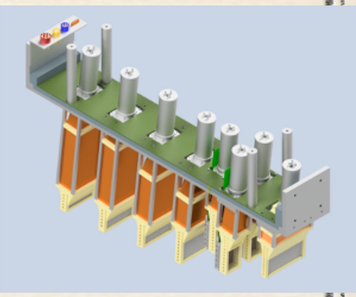








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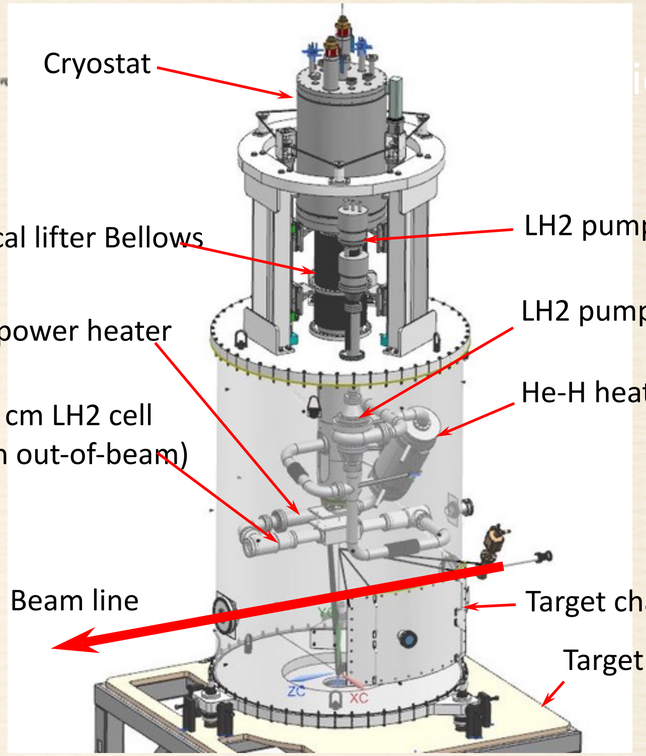
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- up to 70 μA on 125 cm LH_2 target - 3.7 kW
- Q_{weak} experience: use of CFD (computational fluid dynamics)

Main requirement: minimize target density fluctuations ($\Delta\rho/\rho$):

$\Gamma_{target} < 30$ ppm for 70 μA, 5x5 mm^2 raster, 1.92 kHz flip



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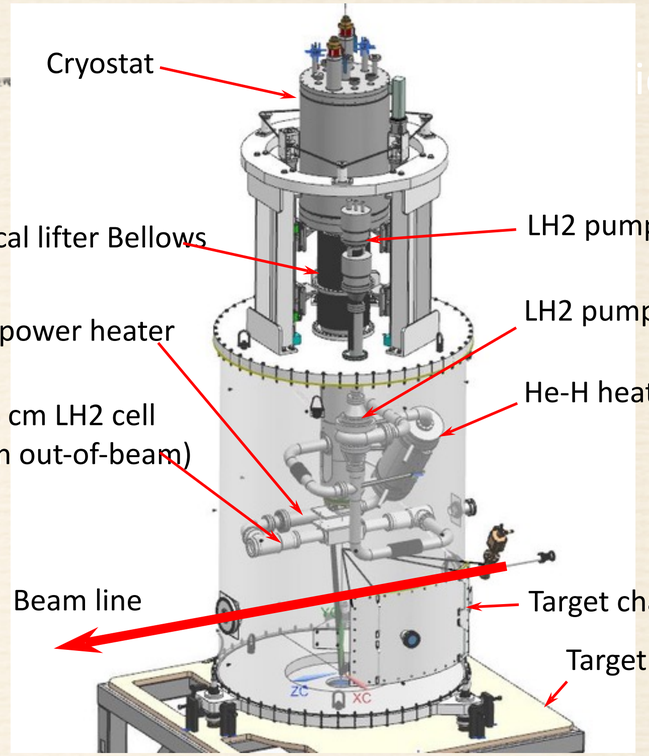
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Test fit of scattering chamber completed

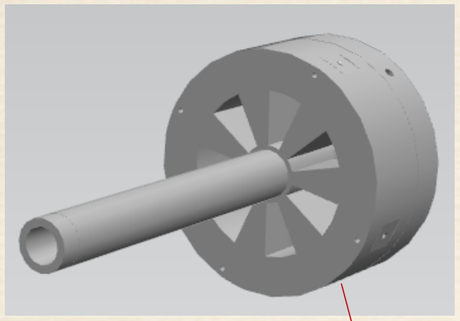






Cryostat components

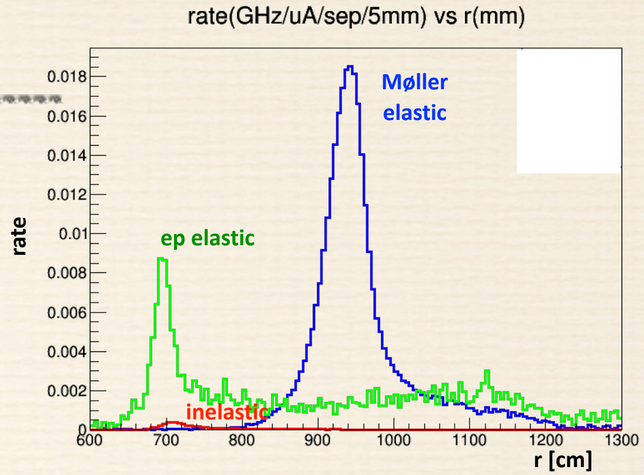
MOLLER Spectrometer

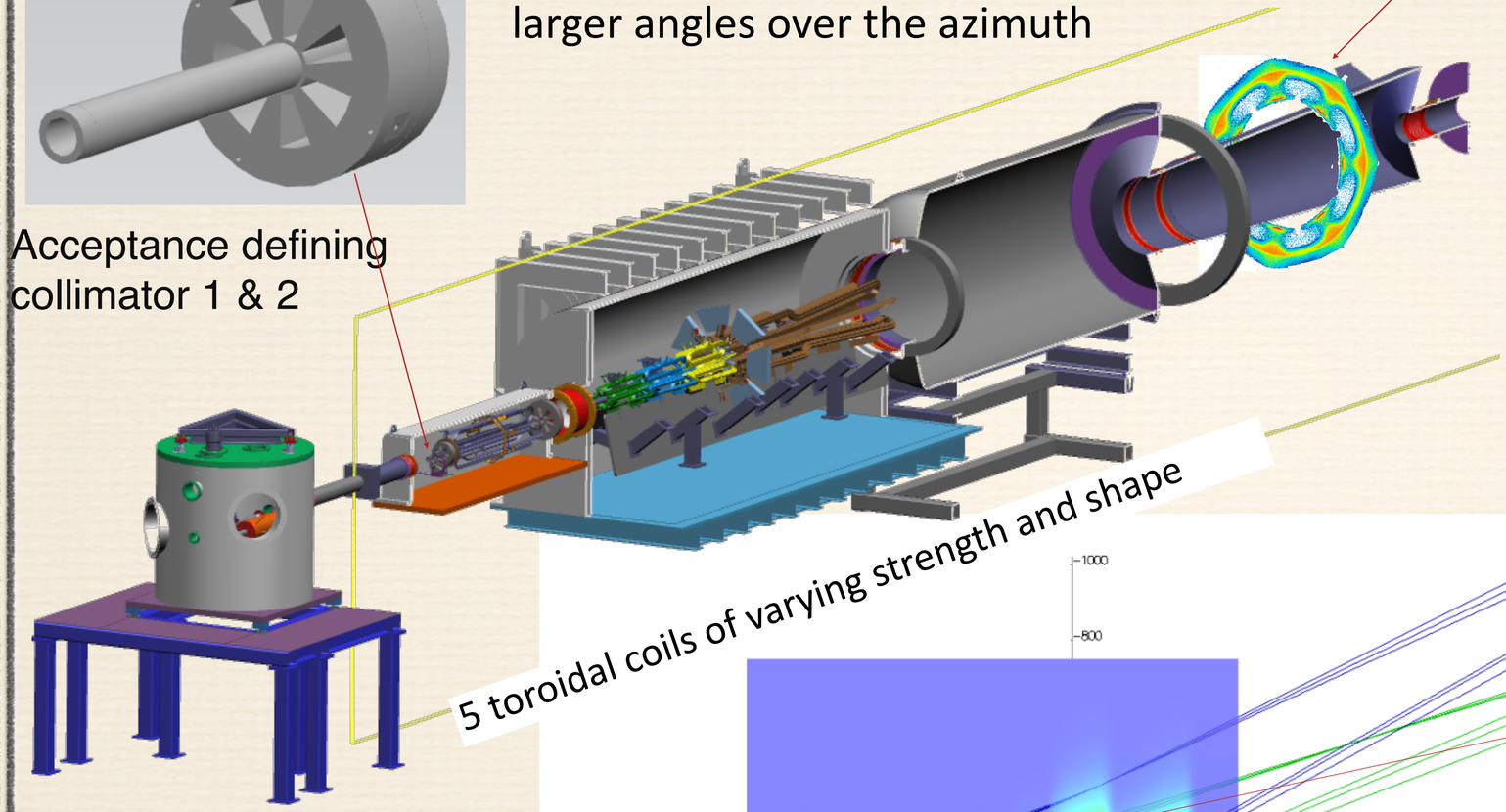


Acceptance defining collimator 1 & 2

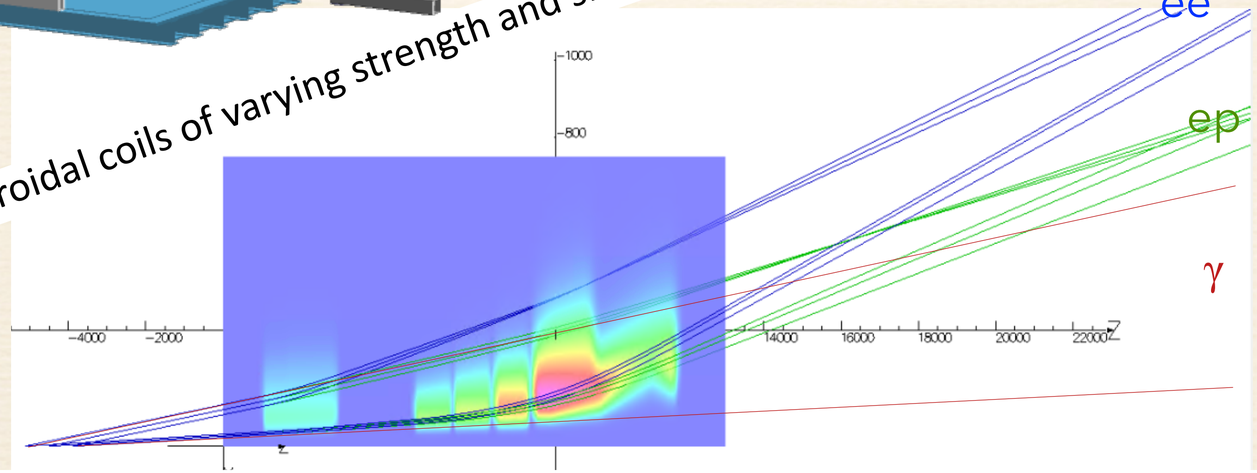
radial field component focuses the smaller angles and stretches the larger angles over the azimuth

flux distribution



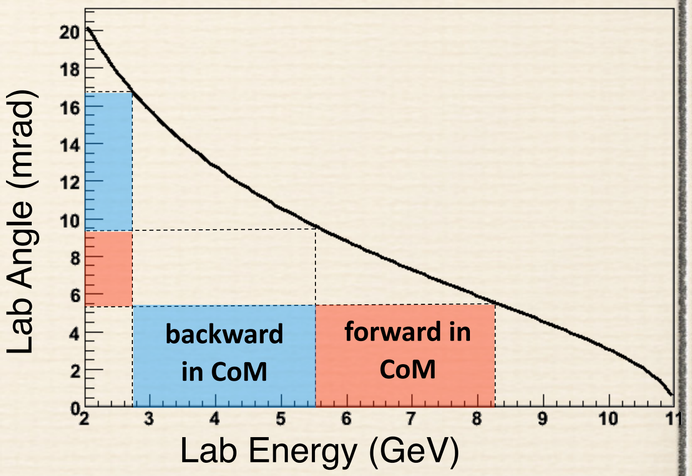


5 toroidal coils of varying strength and shape

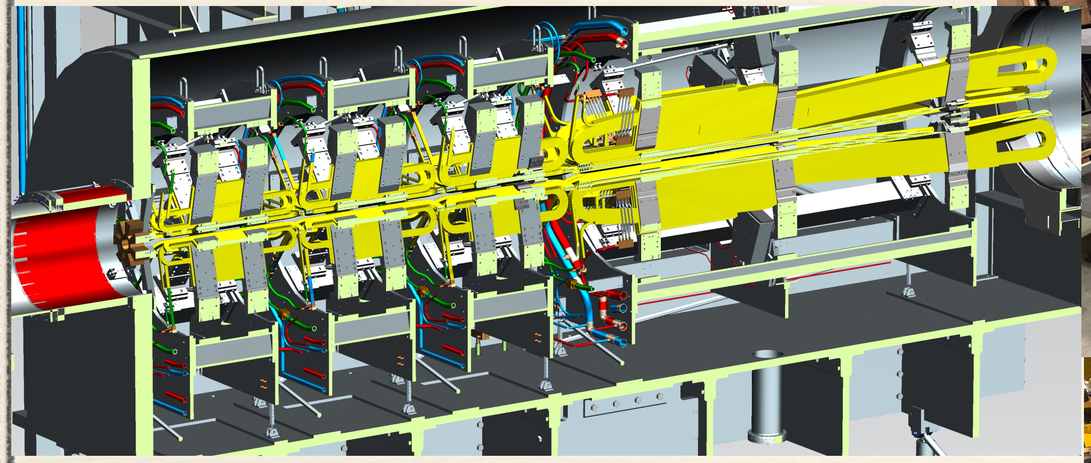


map E-θ correlation for ee scattering to detector

Møller scatters from $5 < \theta_{lab} < 20$ mrad



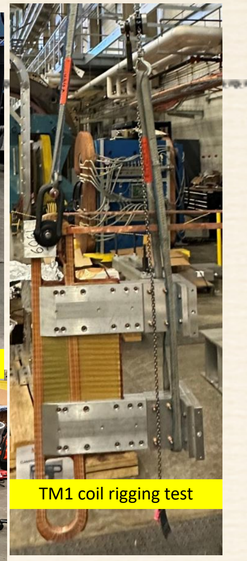
Spectrometer Construction



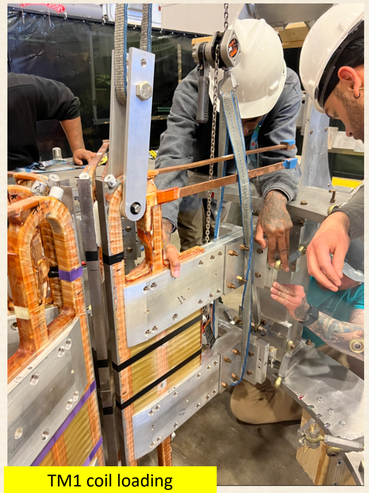


TM2 frame ready for loading

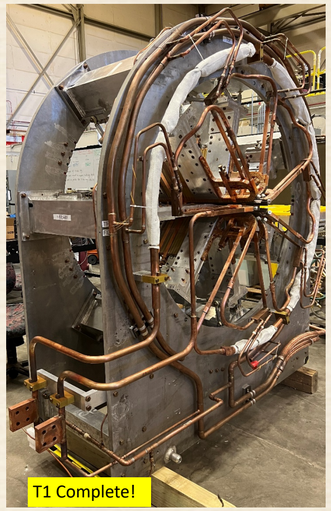




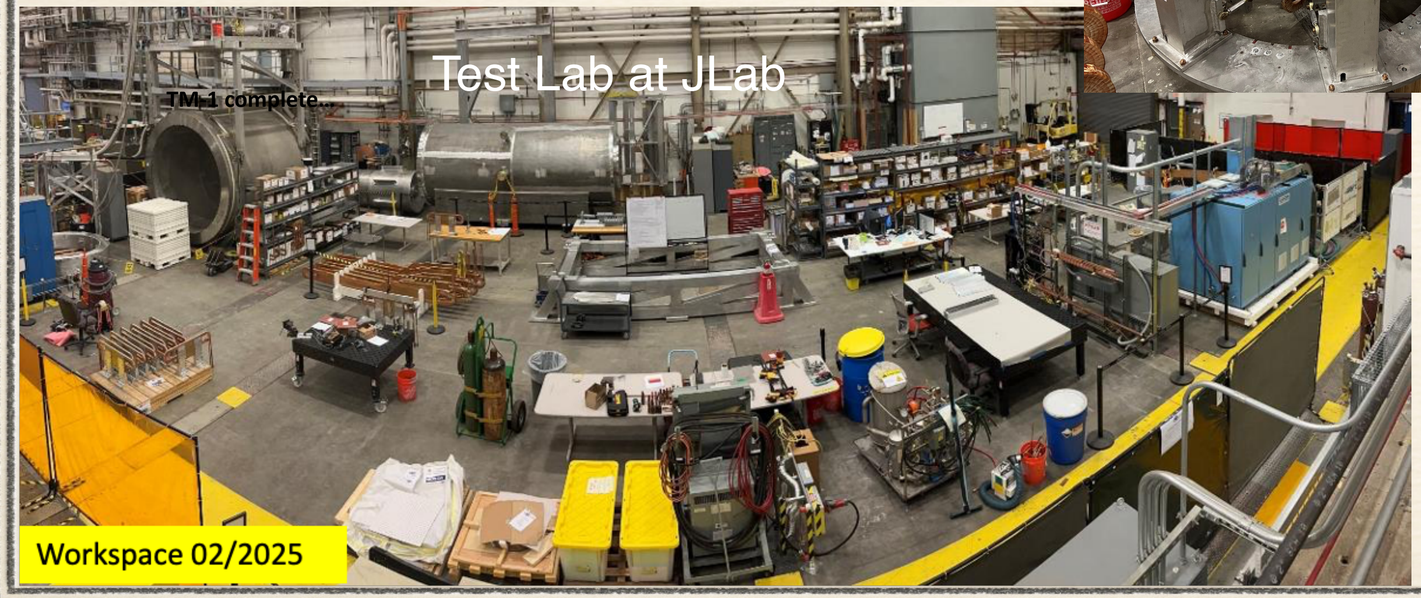
TM1 coil rigging test

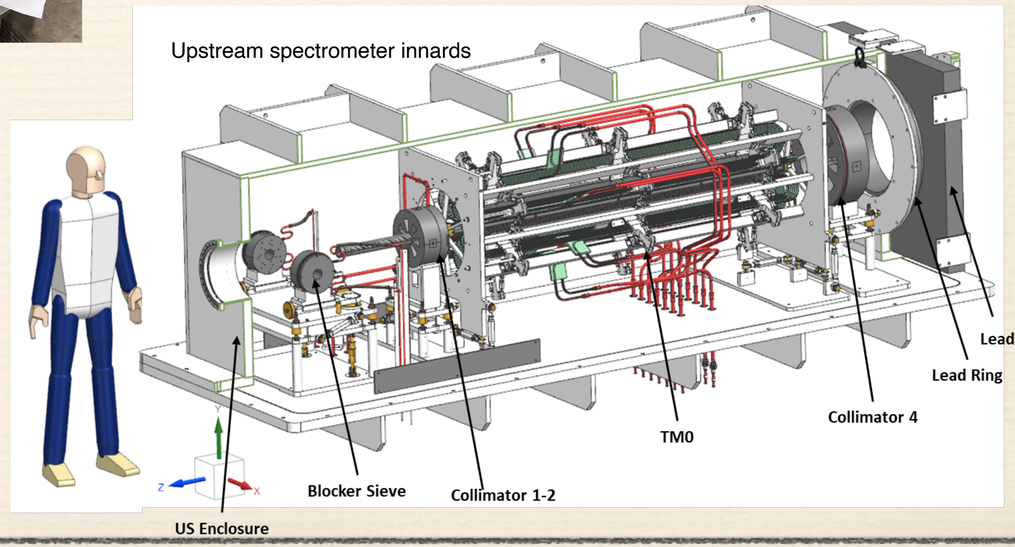


TM1 coil loading



T1 Complete!





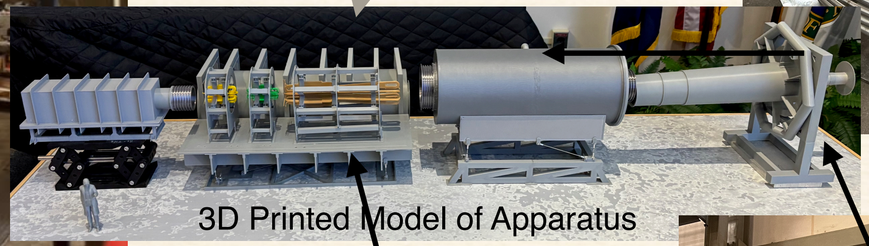
More Construction Pictures

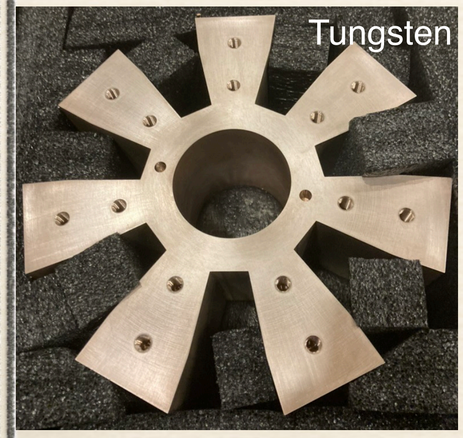


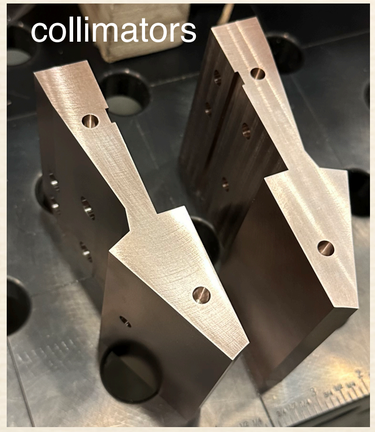






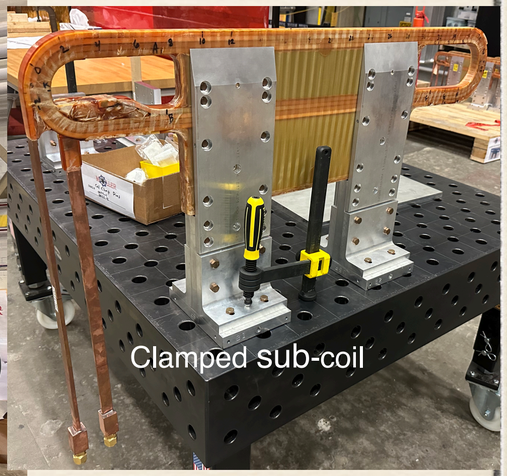




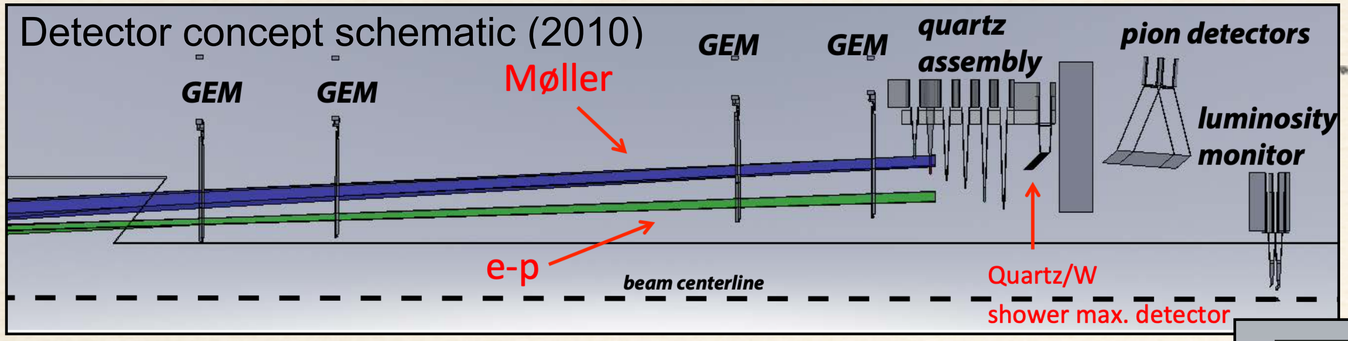








MOLLER Detectors

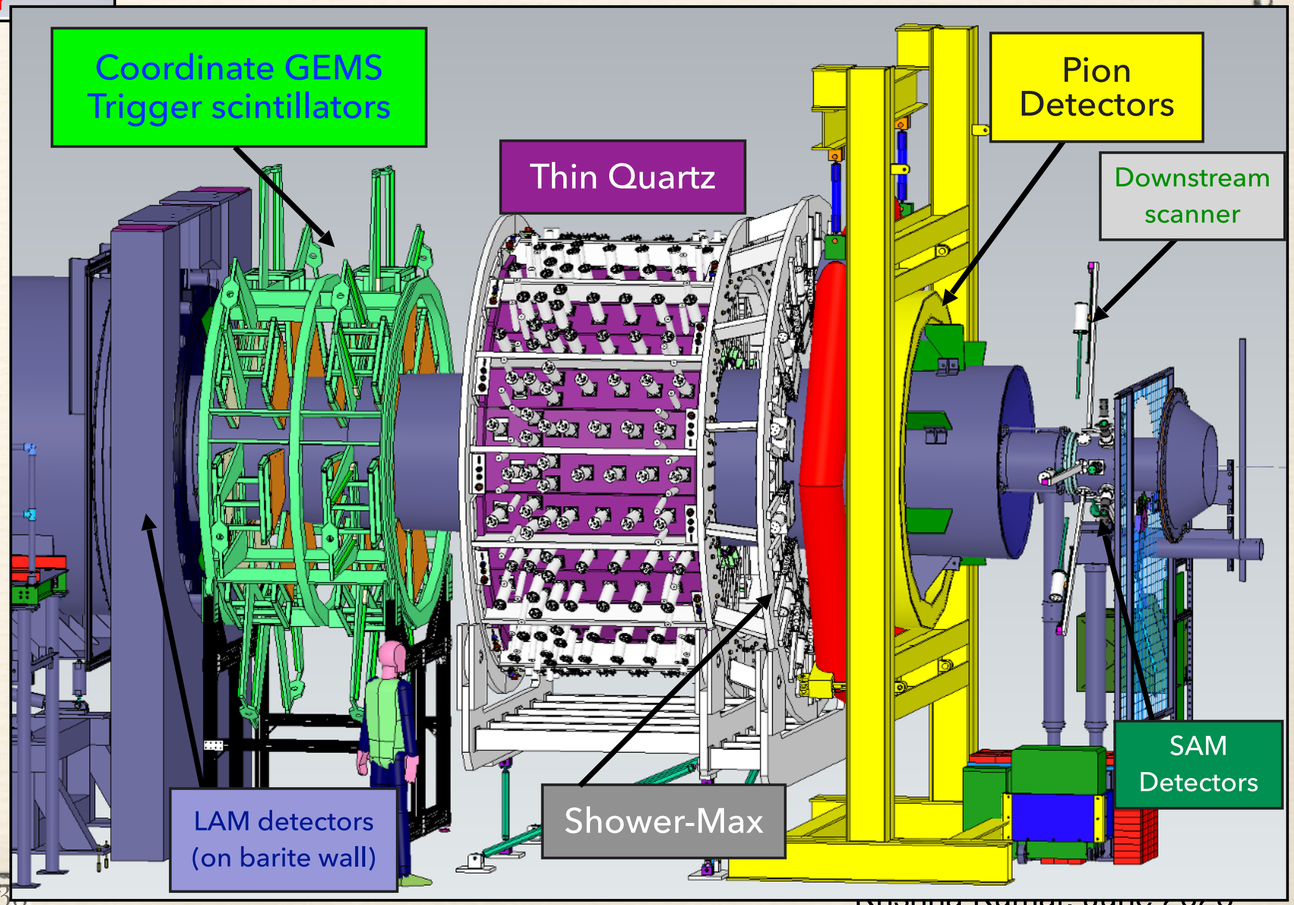


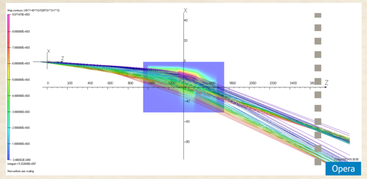
Integrating mode: asymmetry measurement

Counting mode: counting/tracking for calibration

Auxiliary detectors for background and calibration studies

- Intercept the primary electron flux with a radiation hard pure Cherenkov radiator (fused silica or "quartz") with high radial and azimuthal segmentation
- Ensure the required sensitivity to the electron flux asymmetry in the quartz tiles, approaching the shot-noise-limit with little additional background or crosstalk; have a redundant way to measure this asymmetry
- Calibrate the primary electron flux, the irreducible electron background and their relationship to the spectrometer optics and acceptance collimators
- Measure the anticipated few per mille pion/muon background flux rate and asymmetry in the Møller ring
- Monitor the small/large angle and diffuse scattered flux as an additional monitor of beam helicity correlations in the primary beam parameters and the beam halo

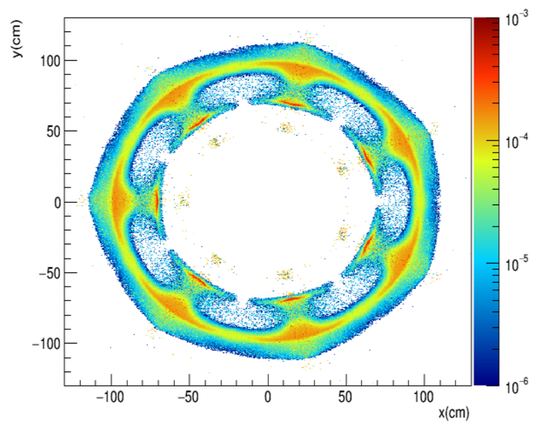




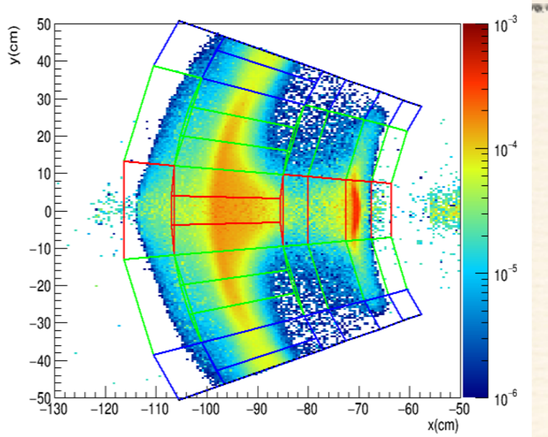
Capturing the Scattered Flux

Time check

Heat map on transverse plane 26.5 m from target center

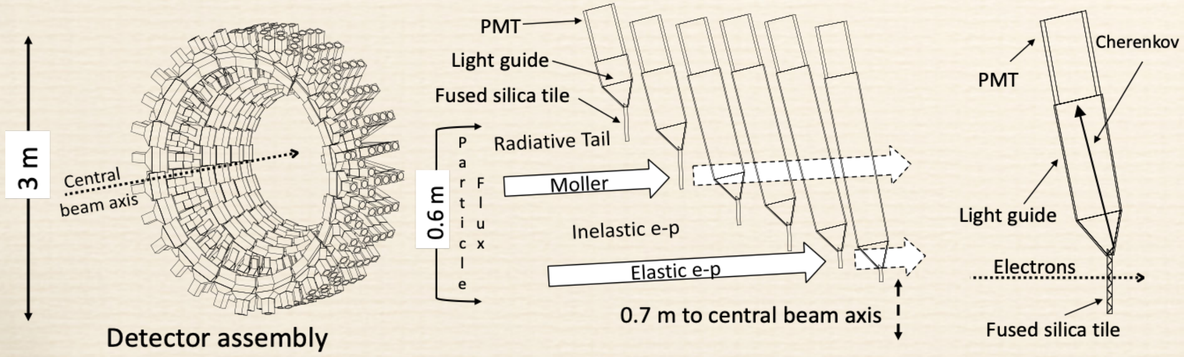


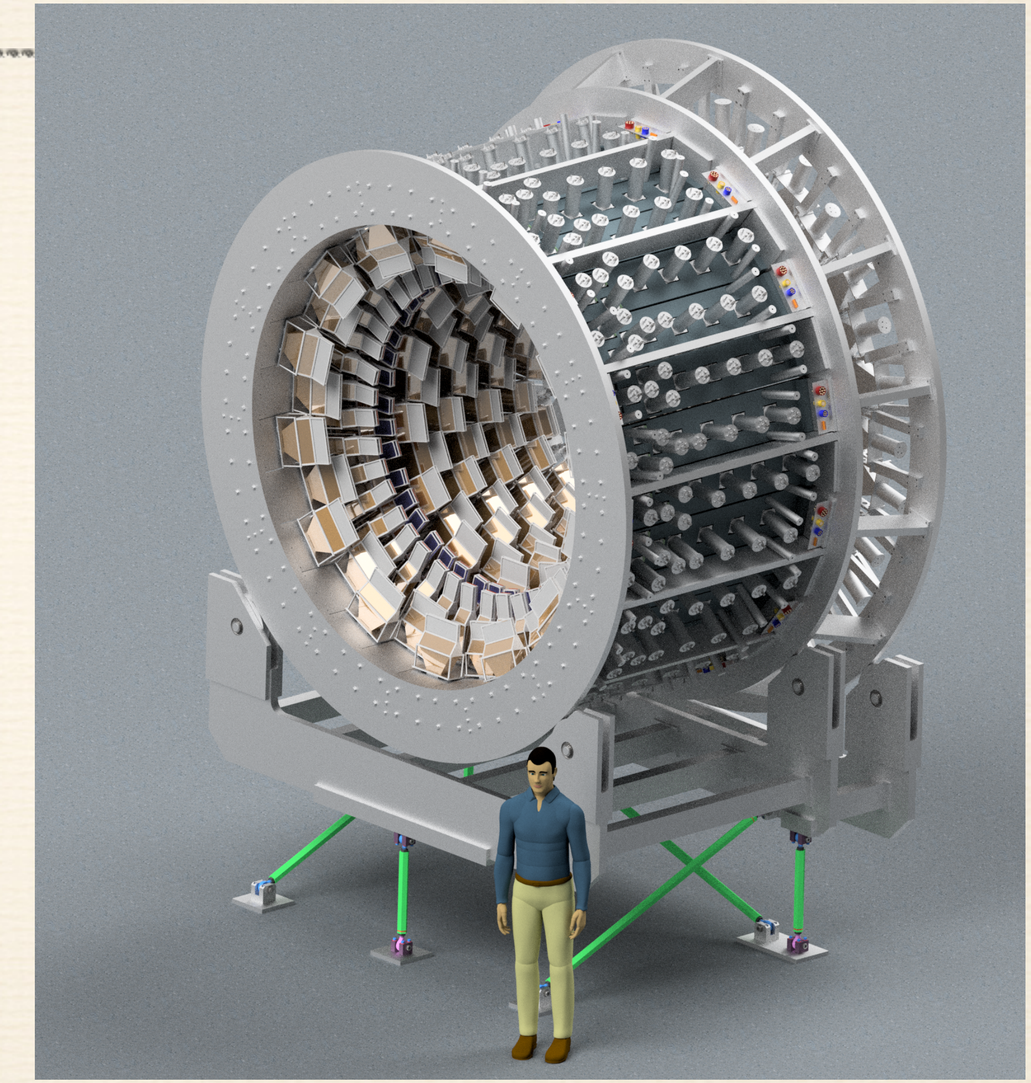
1/7 of the azimuth showing tiling segmentation



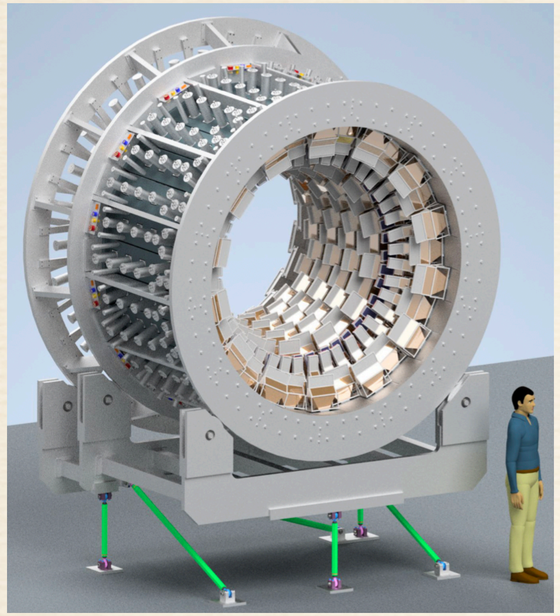
Wide variation in flux intensity and weights of different scattering processes: 1) e-e, 2) elastic e-p, 3) inelastic e-p

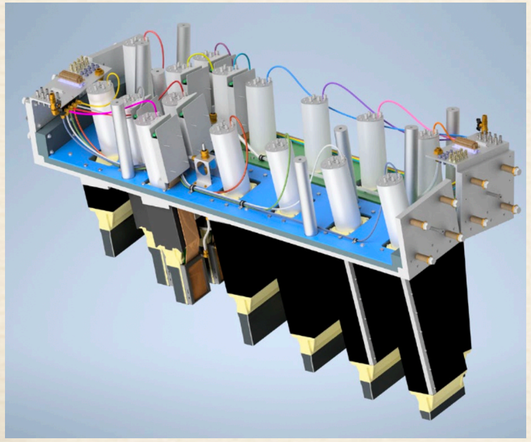
Both radial and azimuthal segmentation in scattered flux measurements required

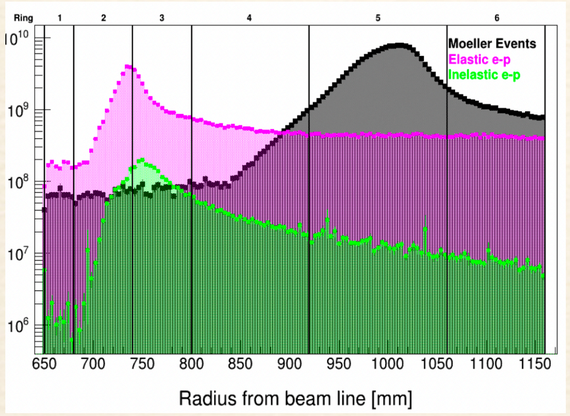




Integrating Detector Assembly

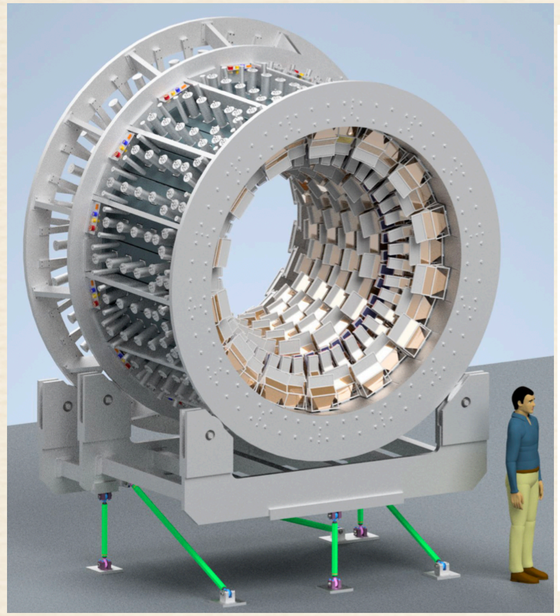


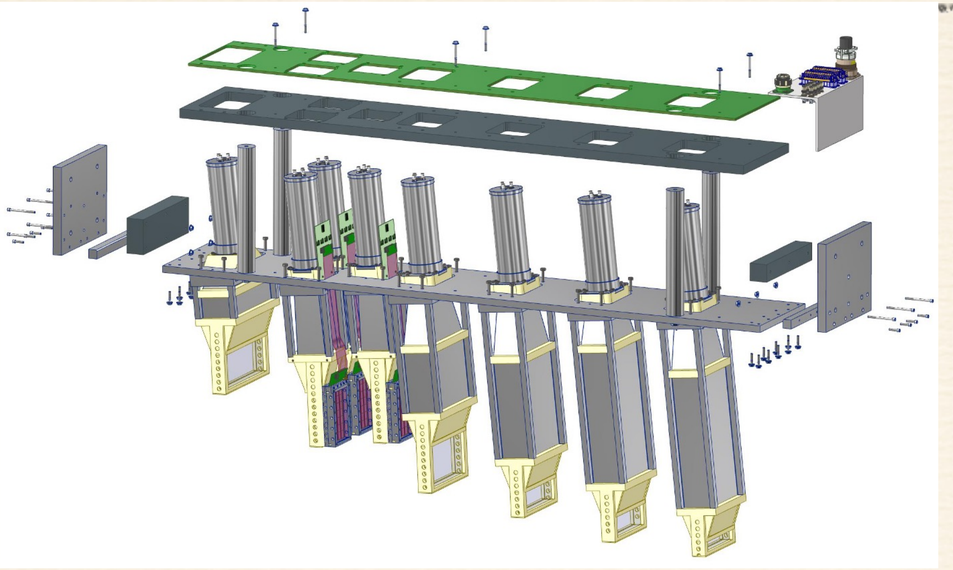


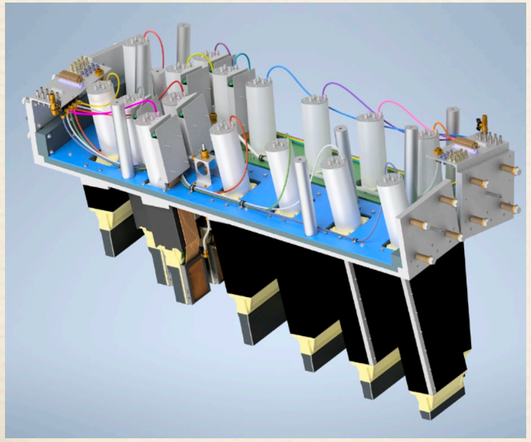


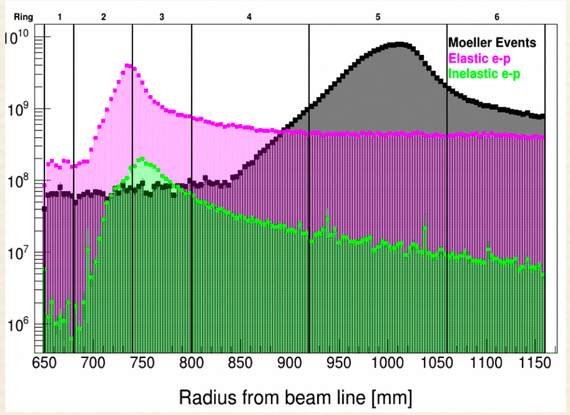
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Integrating Detector Assembly



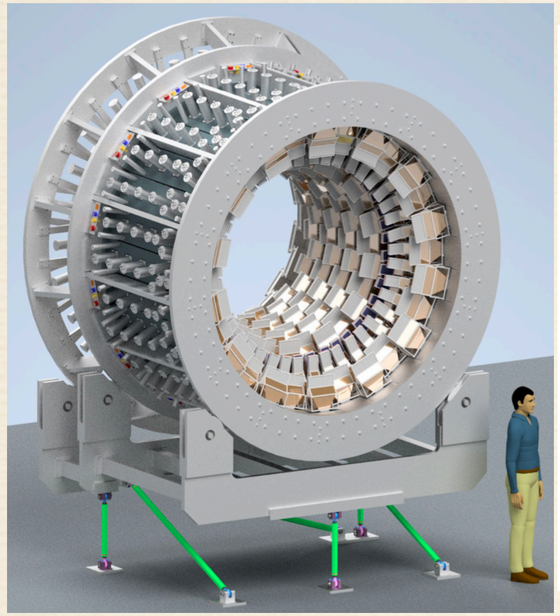


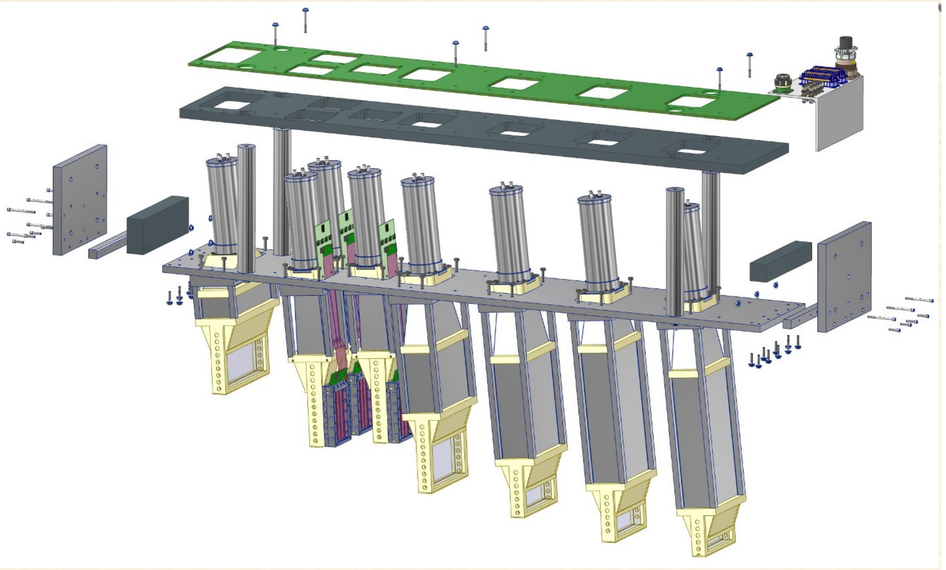


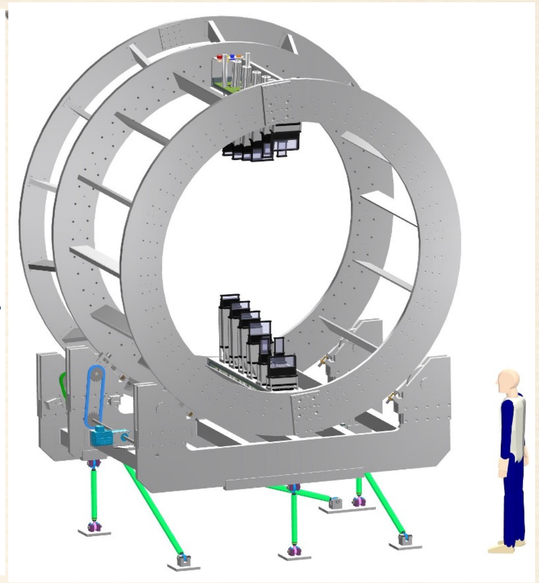


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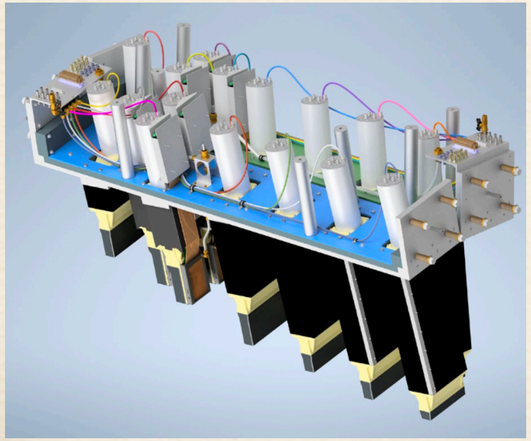
Integrating Detector Assembly

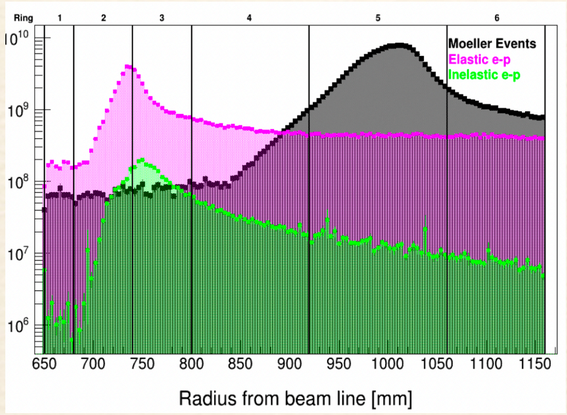




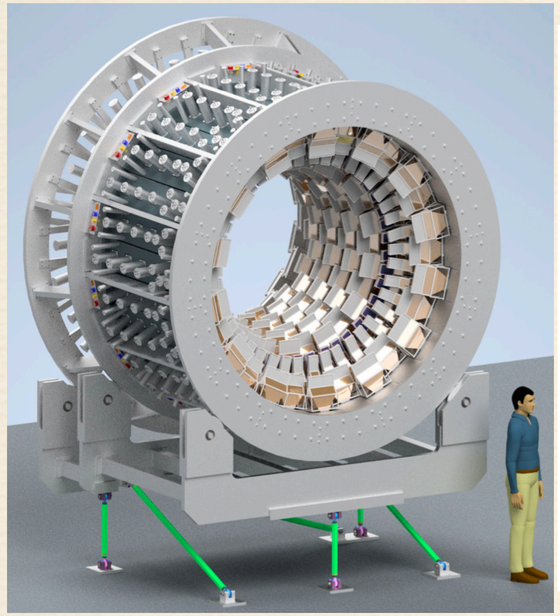


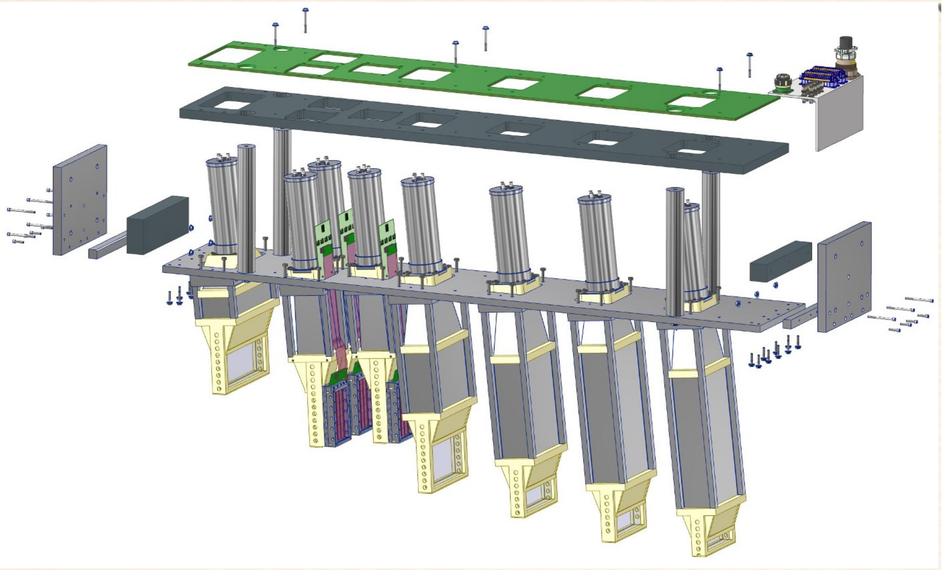
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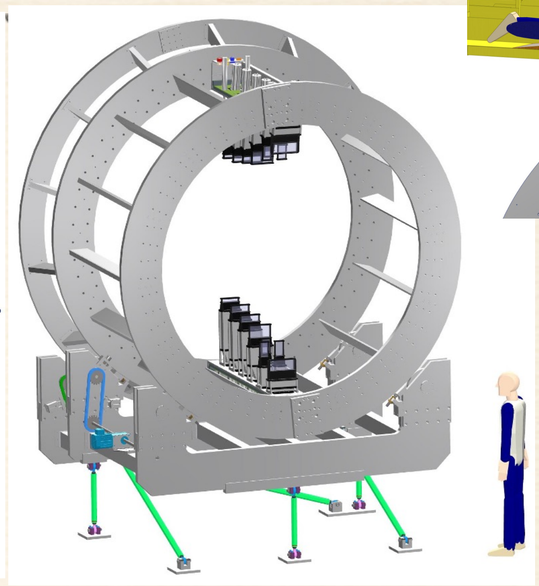


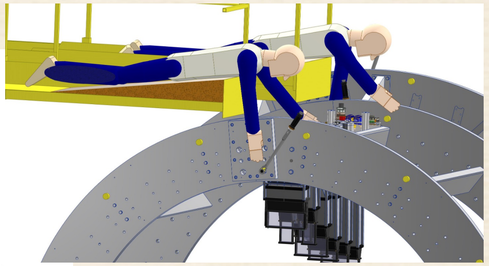


Integrating Detector Assembly

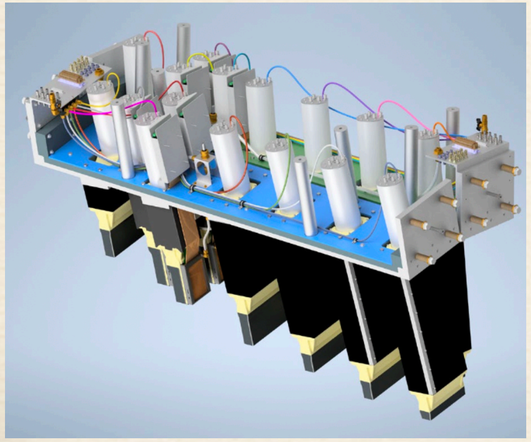


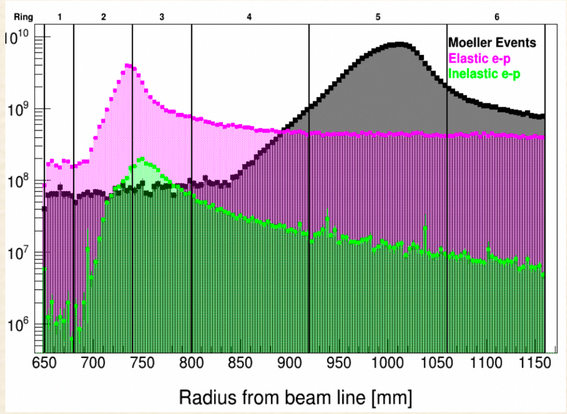




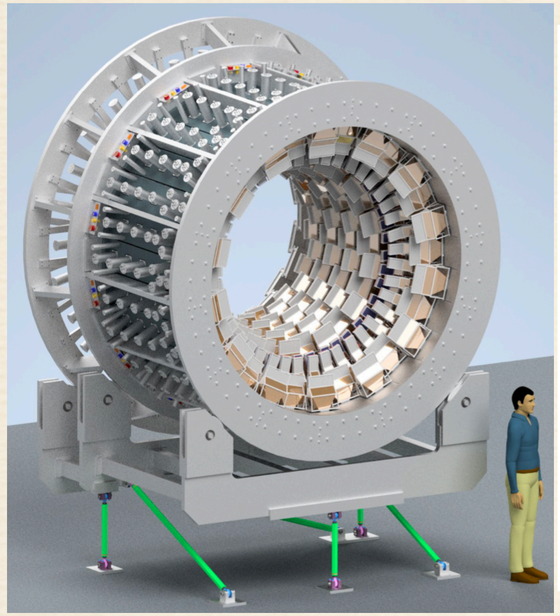


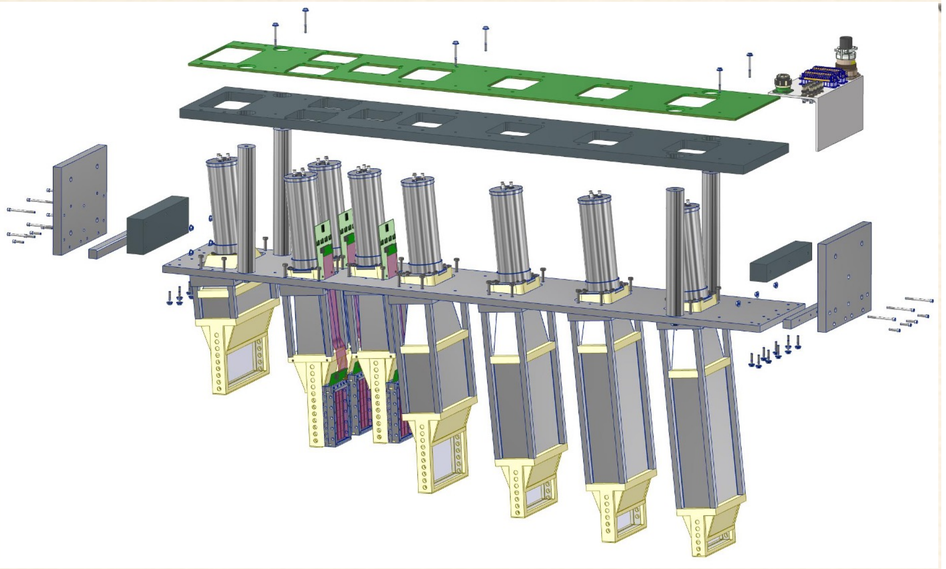
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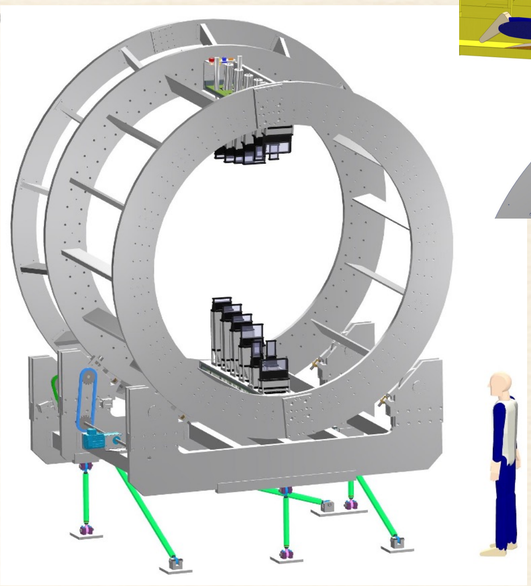


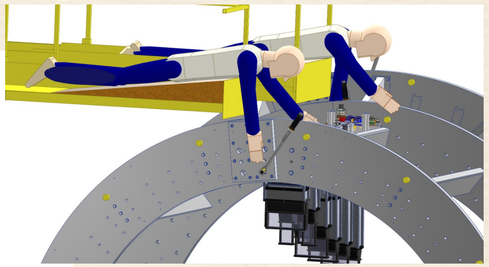


Integrating Detector Assembly

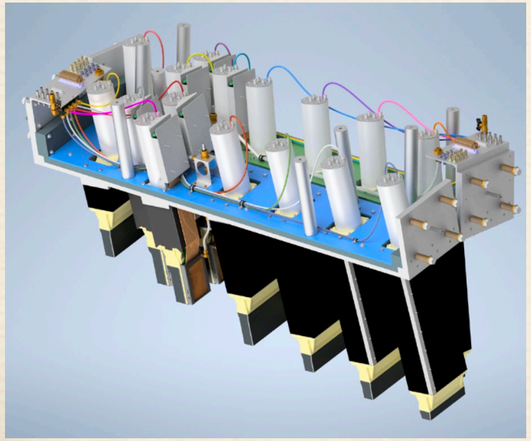


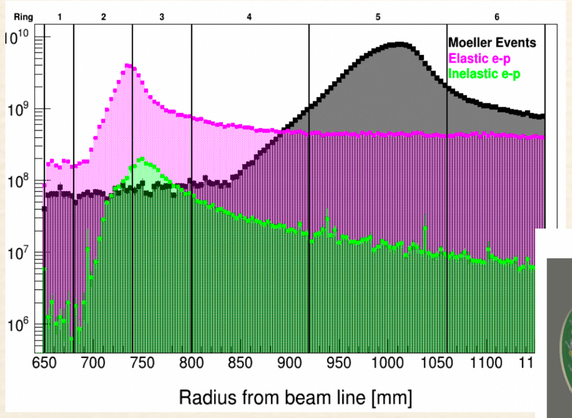


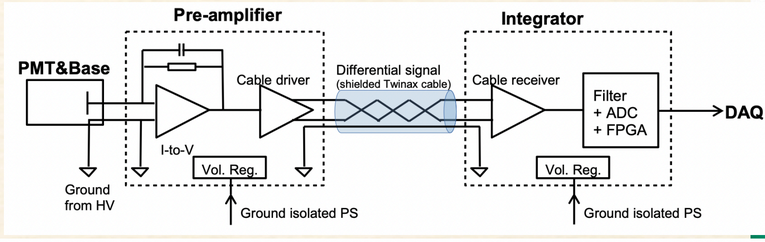


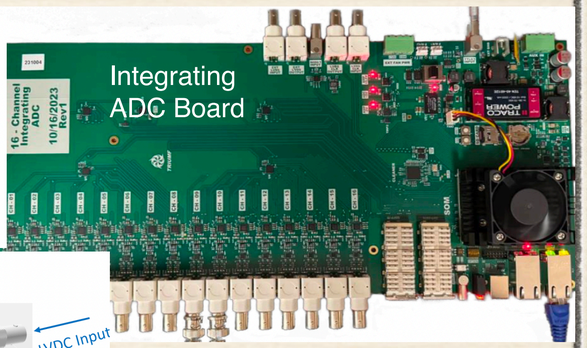


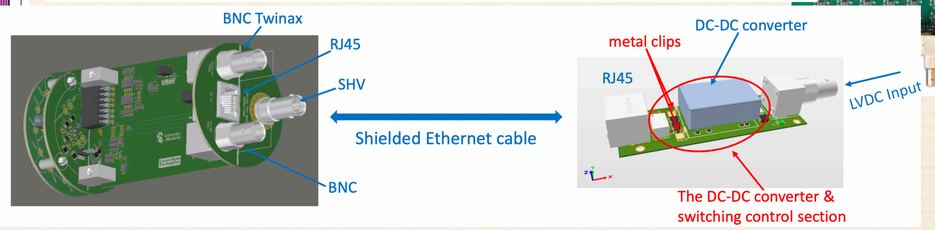
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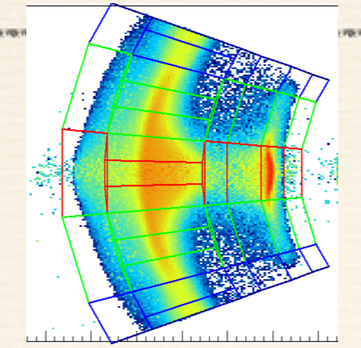






Extracting MOLLER Physics

Inclusive 11 GeV electron scattering off hydrogen

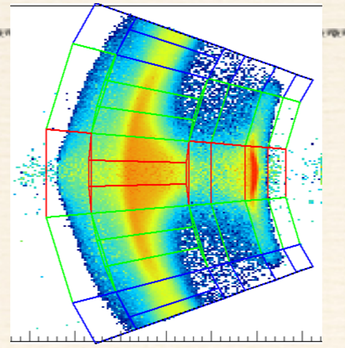


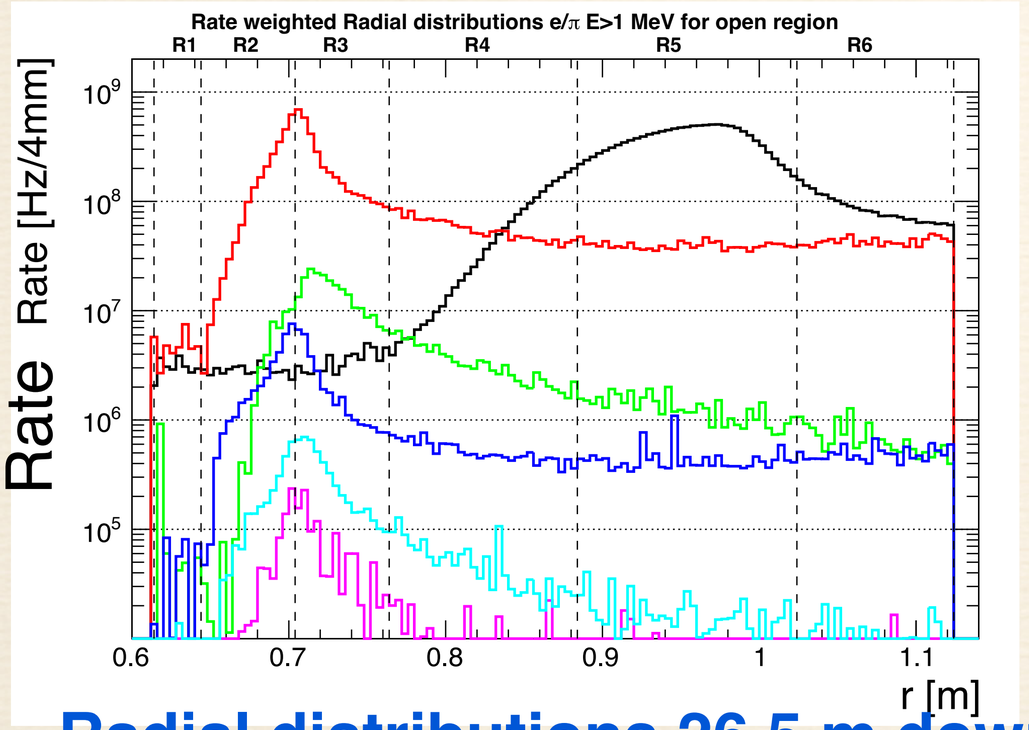
Radial distributions 26.5 m downstream of the liquid hydrogen target

Extracting MOLLER Physics

Inclusive 11 GeV electron scattering off hydrogen

- Black: e-e scattering
- Red: elastic e-p scattering
- Green: inelastic e-p scattering
- Dark blue: elastic e-Al scattering
- Light blue: inelastic e-Al scattering
- Magenta: Al quasi-elastic scattering



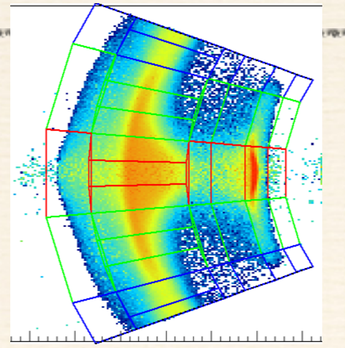


Radial distributions 26.5 m downstream of the liquid hydrogen target

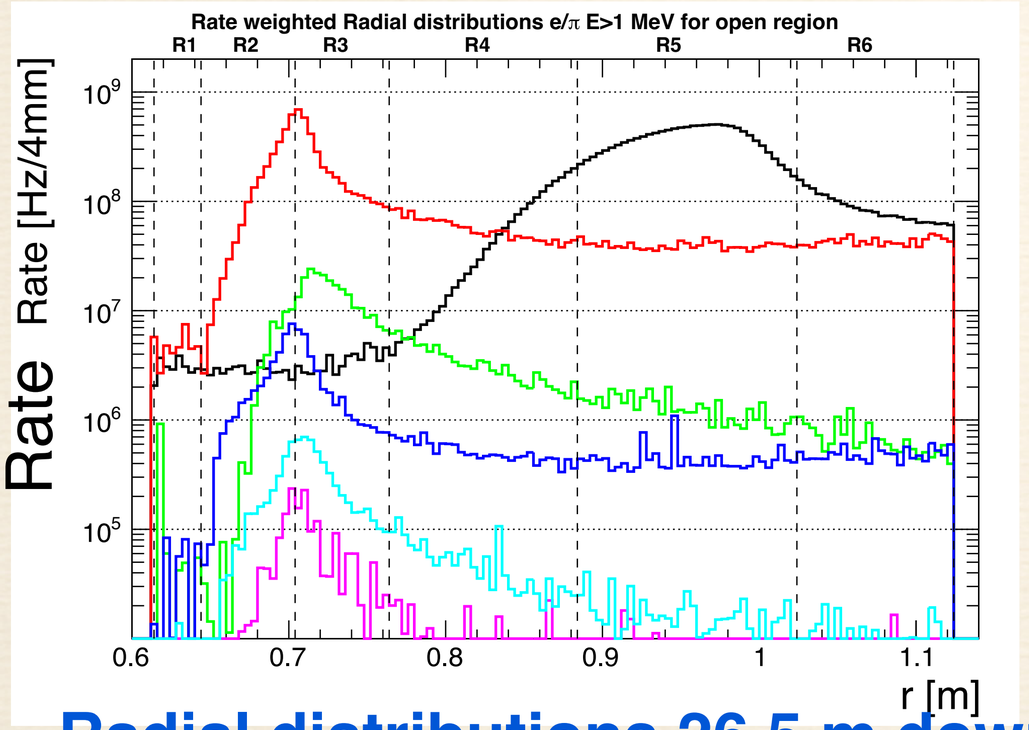
Extracting MOLLER Physics

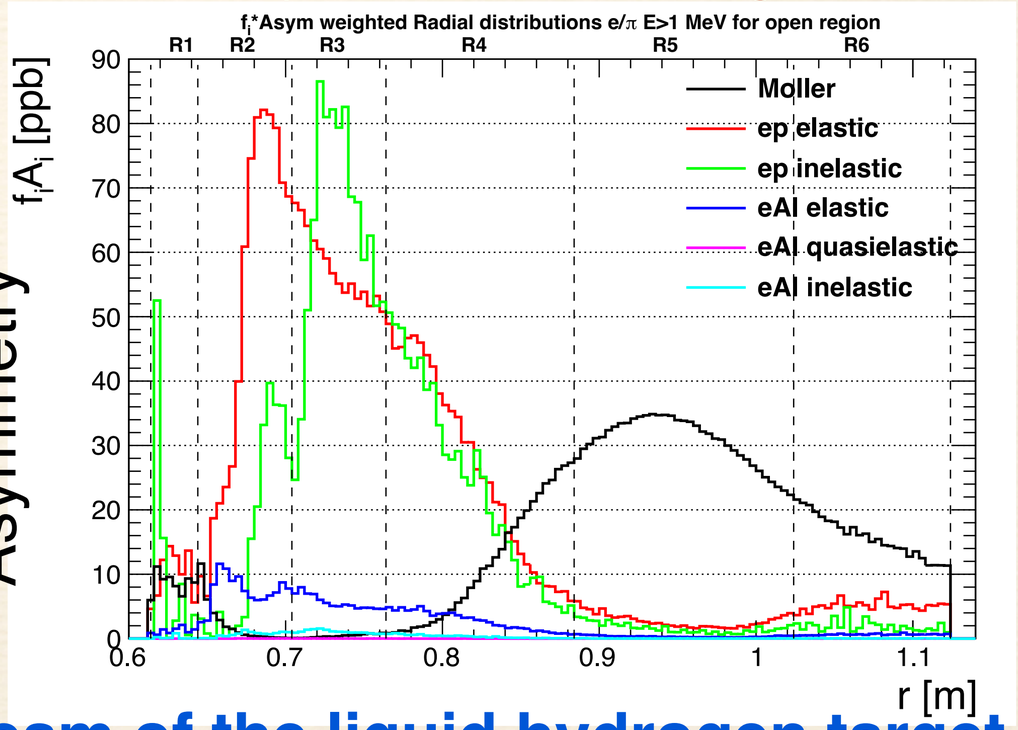
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- Magenta: Al quasi-elastic scattering



- 16 different tile asymmetries
- “Pre-subtract” Al and pion asymmetry contributions
- Simultaneous fit to 16 measurements with different contributions of e-e, e-p elastic, ep-inelastic
- Extract the “weak charge” for e-e, e-p elastic and inelastic e-p for 3 different W ranges





Radial distributions 26.5 m downstream of the liquid hydrogen target

PV Electron-Proton Inelastic

Assumption: $A_{PV}/Q^2 \sim F(W)$ is constant in 3 W regions

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Mock Fit Extraction with Monte Carlo Trial Data Fit

Processes	Expected A (ppb)	σ_A (ppb)	$\frac{\sigma_A}{\lvert A \rvert}$ (%)
Moller	-35.20	0.64	1.8
ep-elastic	-19.67	1.82	9.2
ep-inelastic (1)	-439.94	80.6	18.3
ep-inelastic (2)	-433.96	38.3	8.8
ep-inelastic (3)	-384.59	91.5	23.8
eAl-elastic	297.27	83.01	27.9

Corrections for Ring-5 Tiles after Fit Extraction

Process	Correction (%)	Systematic Error (%)
e-p elastic	1.14	0.08
e-p inelastic ($W < 1.4$ GeV)	-1.34	0.22
e-p inelastic ($1.4 < W < 2.5$ GeV)	-1.54	0.11
e-p inelastic ($W > 2.5$ GeV)	-1.66	0.35
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Deep inelastic scattering

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

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first principles: using electroweak neutral current structure functions

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

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MOLLER kinematics: **E_{beam} = 11 GeV, $6 < \theta_{lab} < 20$ mrad, E' = 3 to 8 GeV**

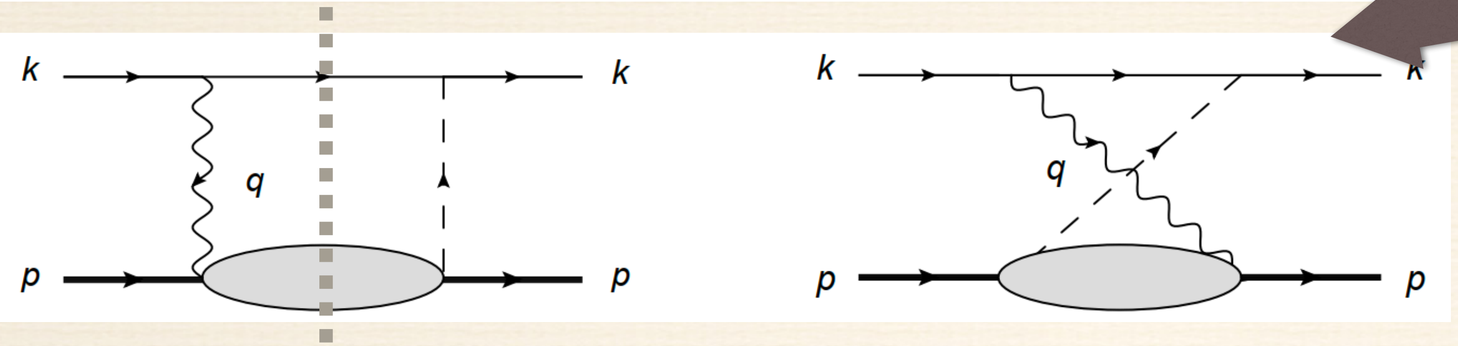
Q^2 ~ 0.001 - 0.02 GeV^2, W^2 from 1 to 20 GeV^2

Diffractive Regime (VMD or Pomeron Physics)

Proton Weak Charge Box

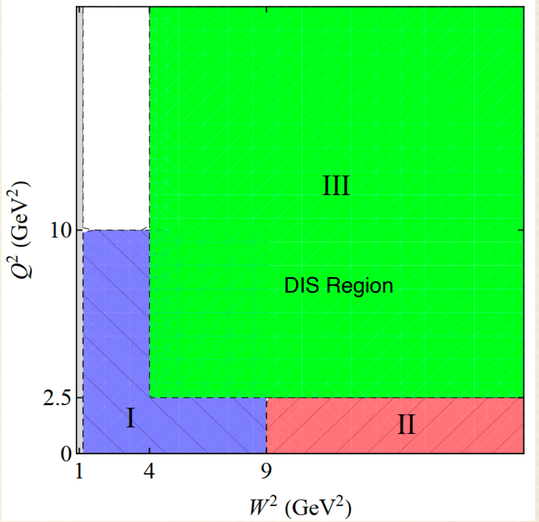
Radiative corrections to the theoretical prediction of the weak charge of the proton

$$Q_W^p = (1 + \Delta\rho + \Delta_e)\left(1 - 4\sin^2\theta_W(0) + \Delta_e'\right) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}(0)$$



$F_{1,2}^{\gamma Z}(Q^2, W^2)$

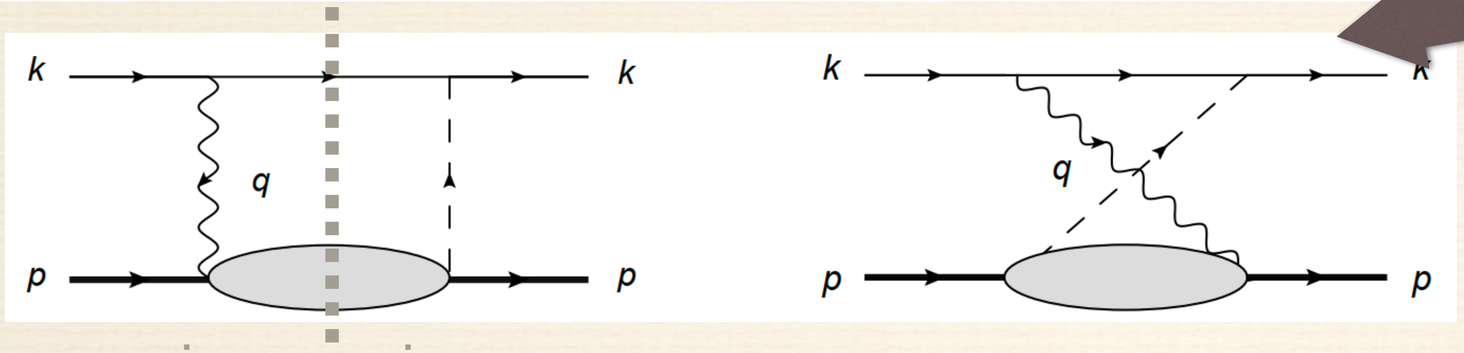
In 3 different kinematic regimes



Proton Weak Charge Box

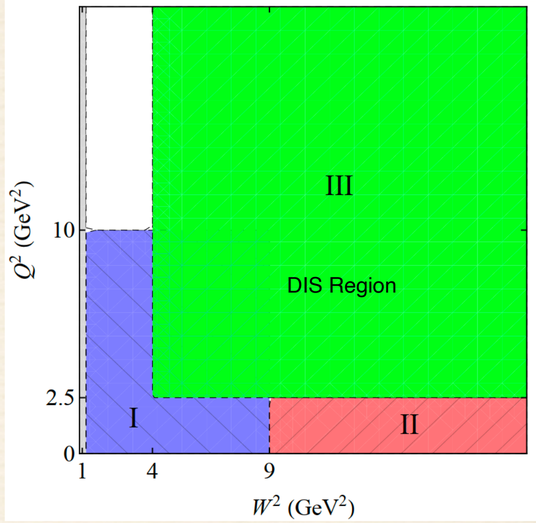
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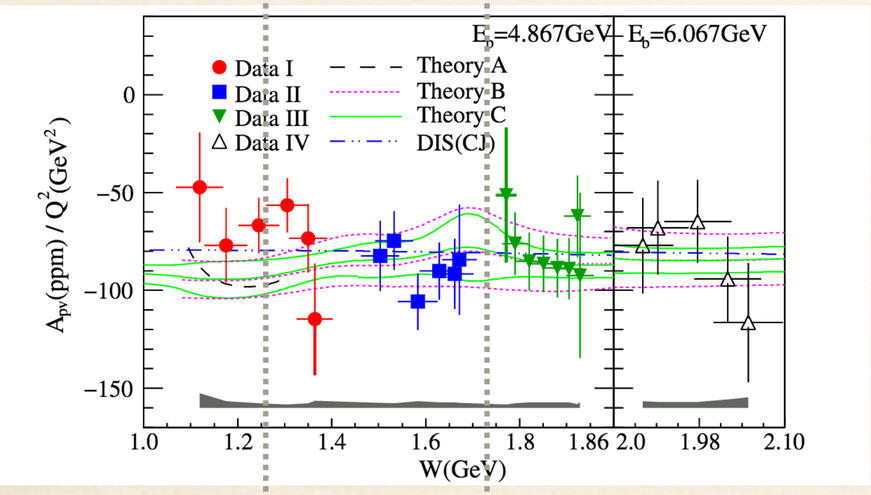
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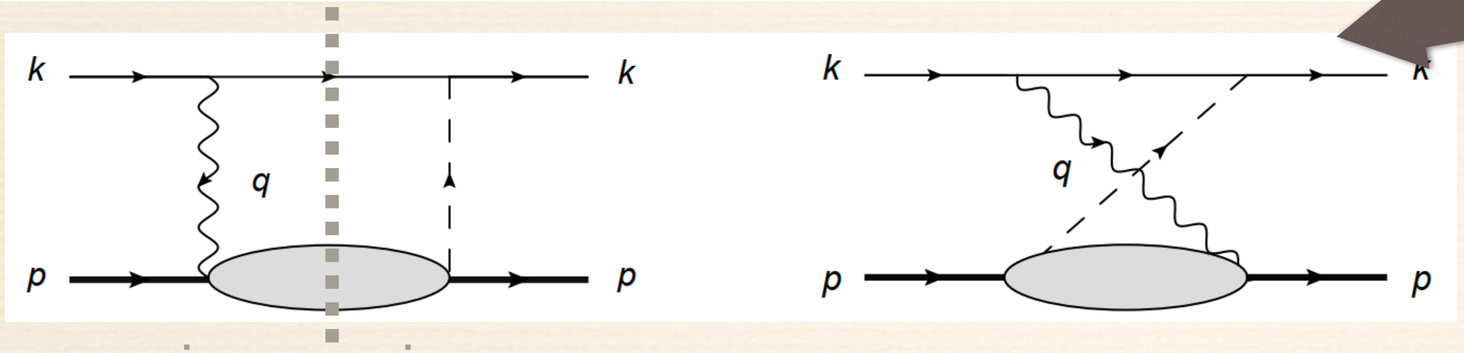


Matsui et al, Gorshtein et al, AJM, CJ, compared to PVDIS measurements

Proton Weak Charge Box

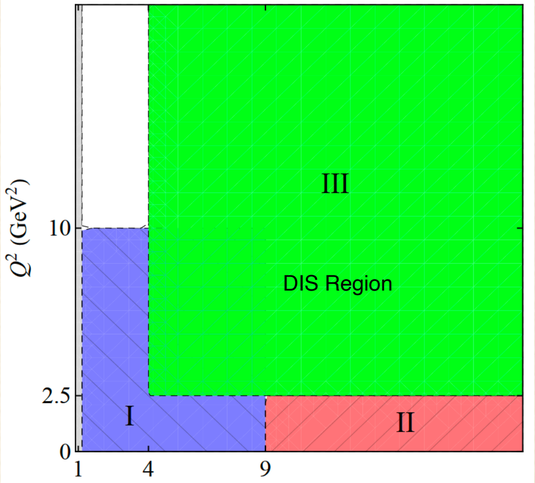
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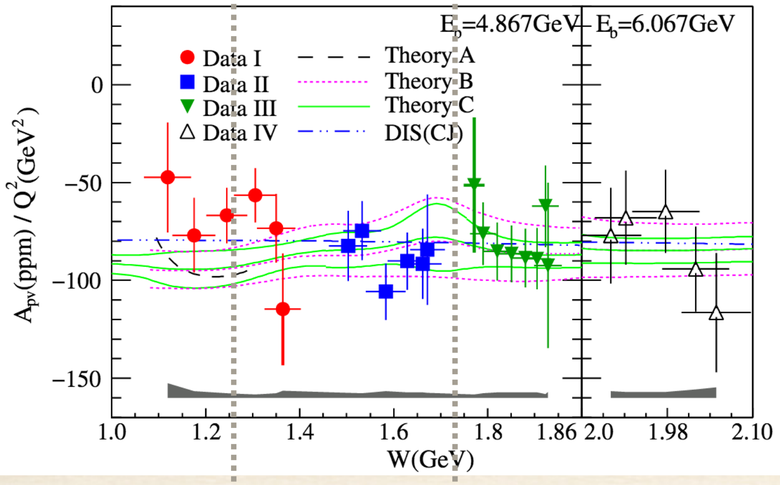
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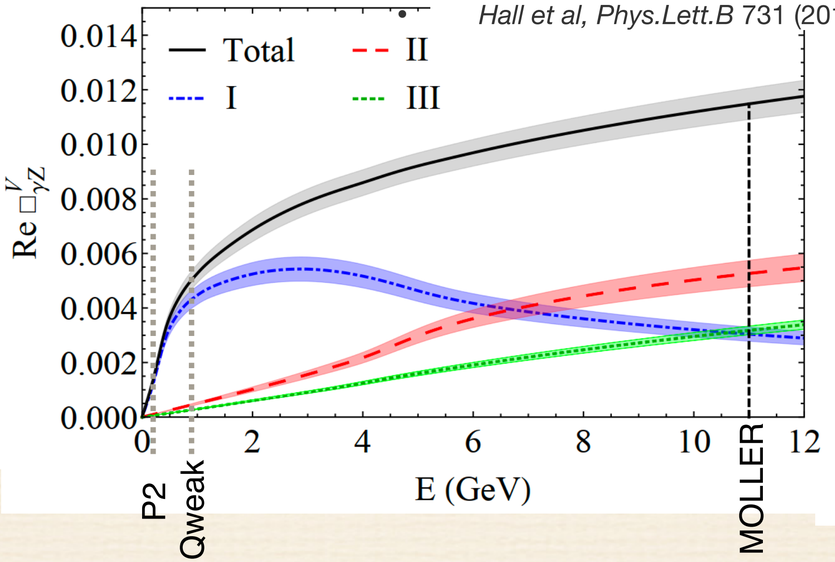
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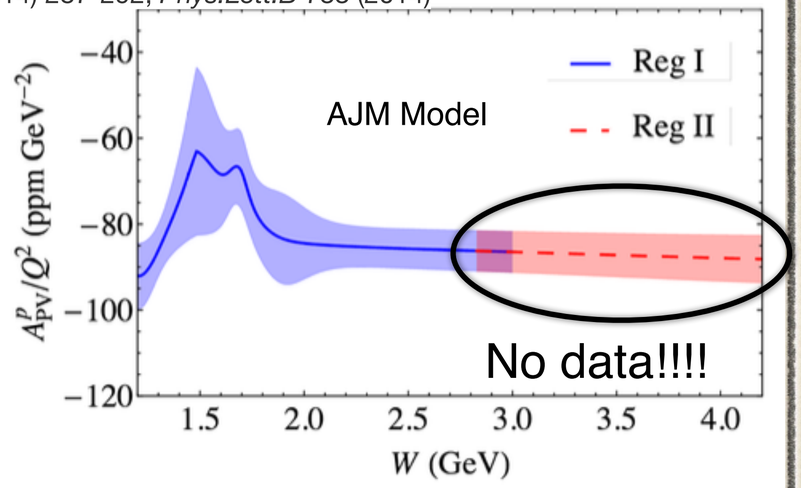




Matsui et al, Gorshtein et al, AJM, CJ, compared to PVDIS measurements

Hall et al, Phys.Lett.B 731 (2014) 287-292, *Phys.Lett.B* 733 (2014)

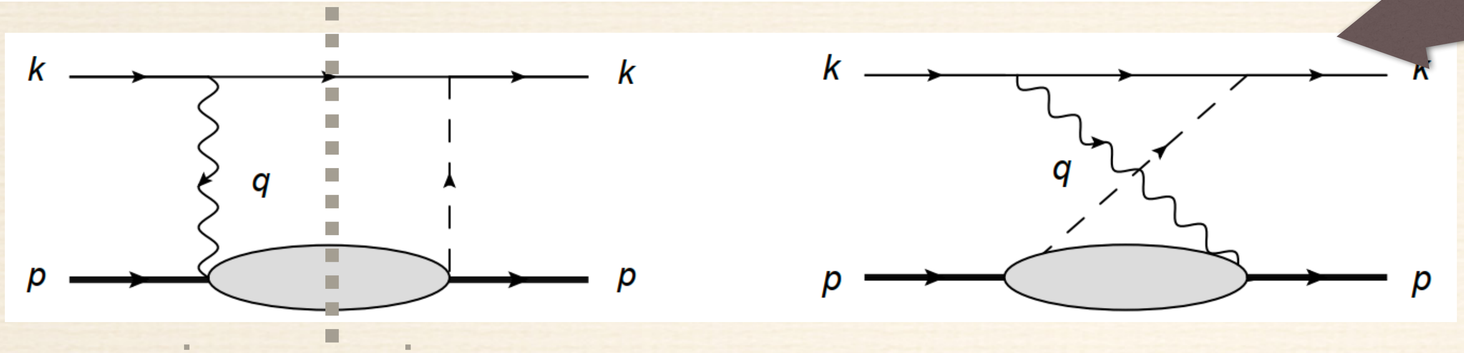




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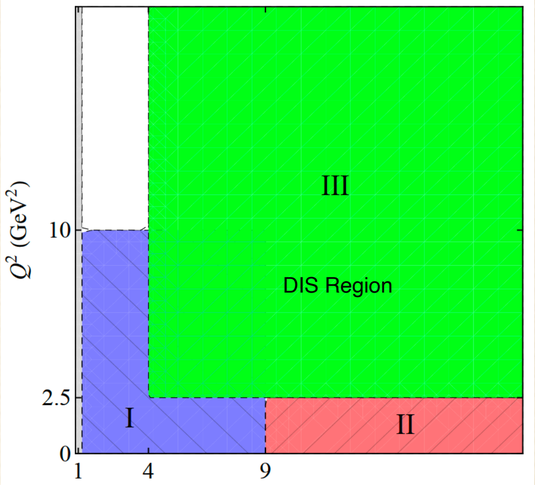
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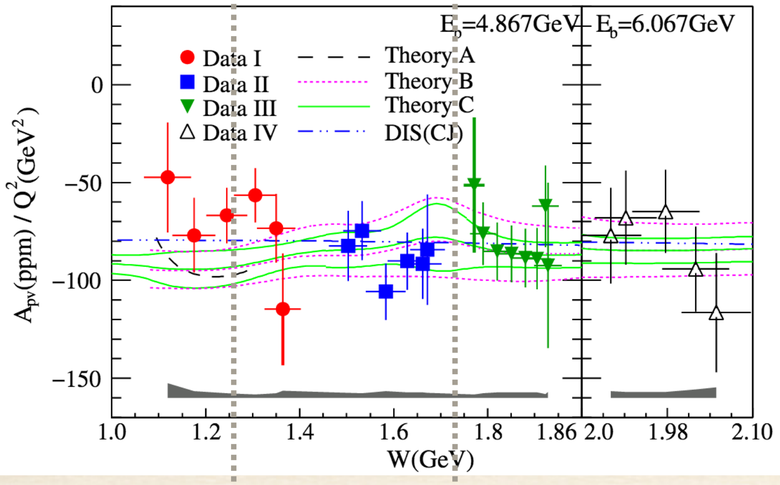
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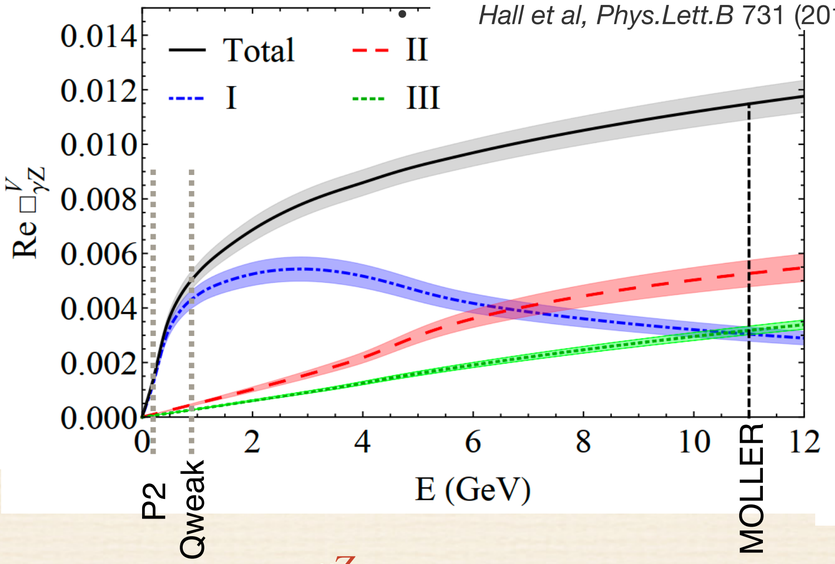
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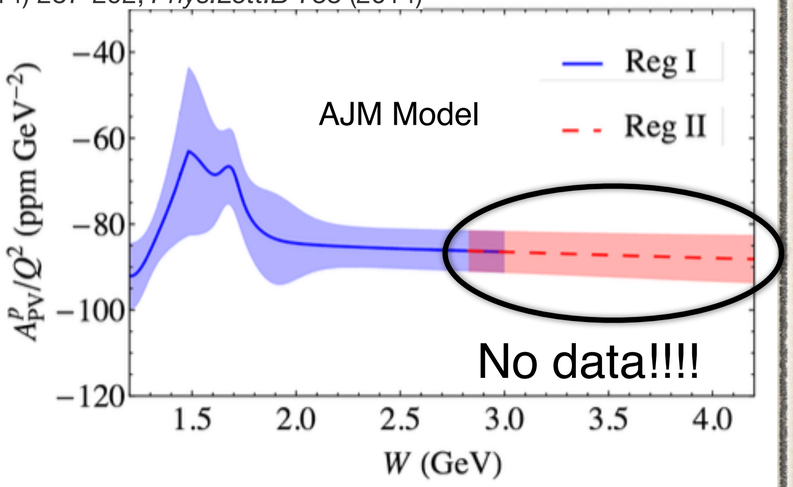




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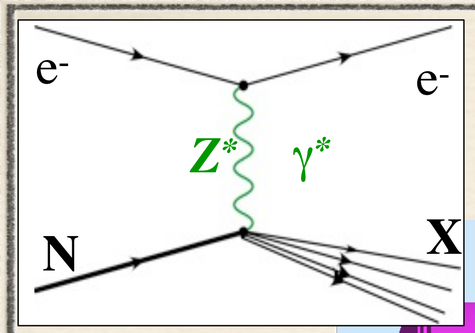
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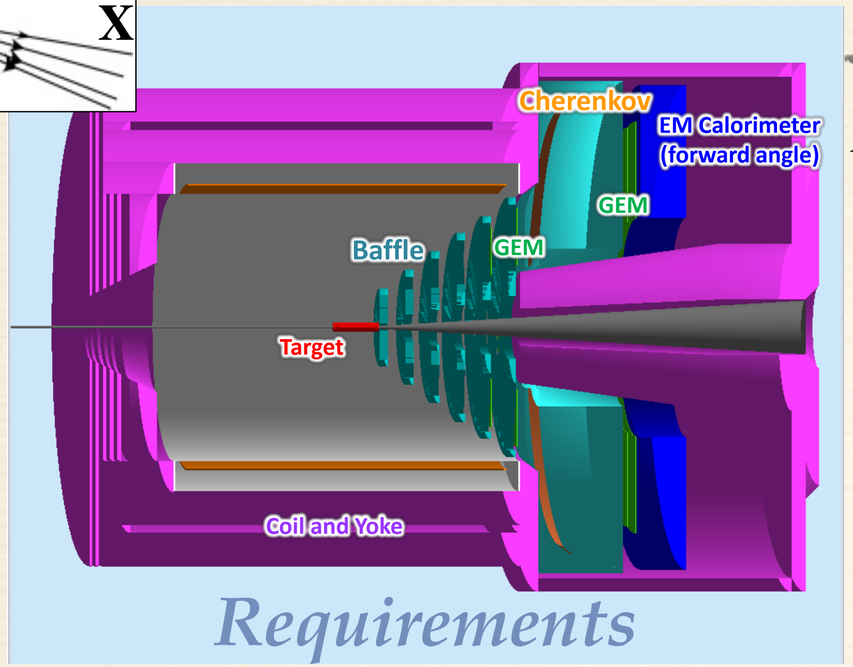




There is no data on $F_1^{\gamma Z}$ in Region II! MOLLER will make the first ever measurement!

PVDIS at 12 GeV: SOLID





$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)\,b(x)\right]$$

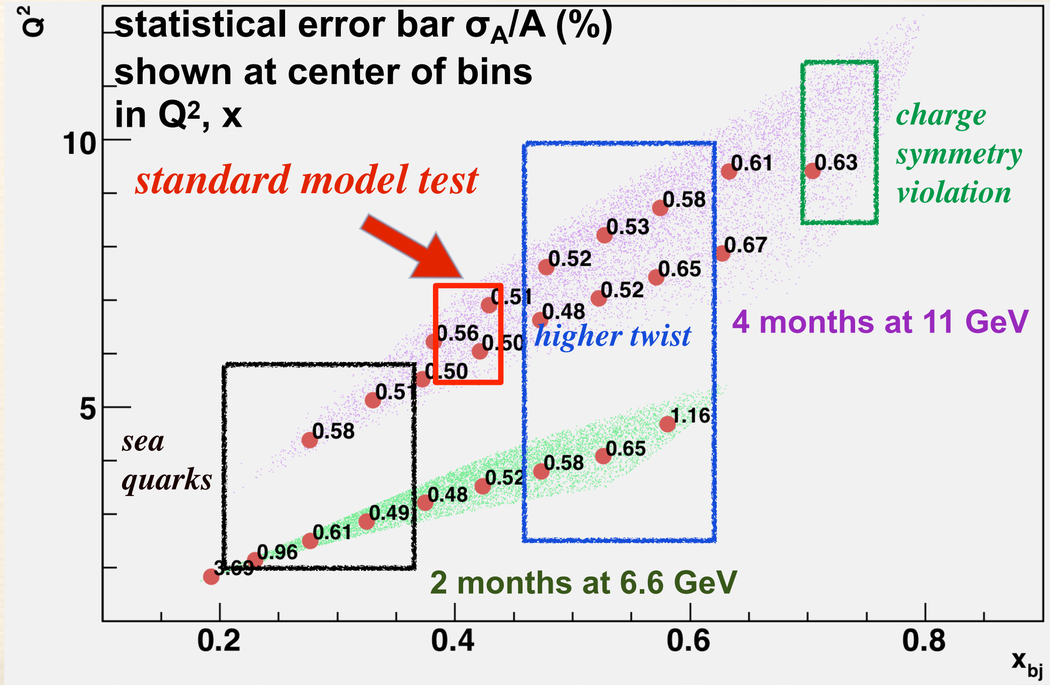
a(x): function of C_{1i}'s

b(x): function of C_{2i}'s

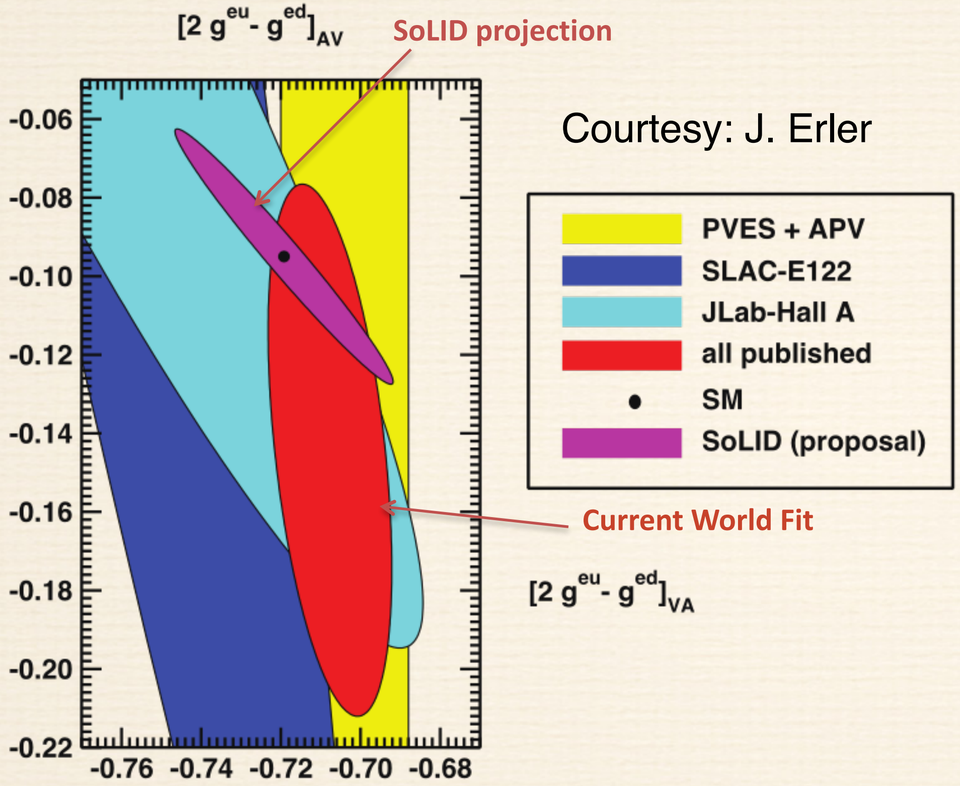
Strategy: **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

Requirements

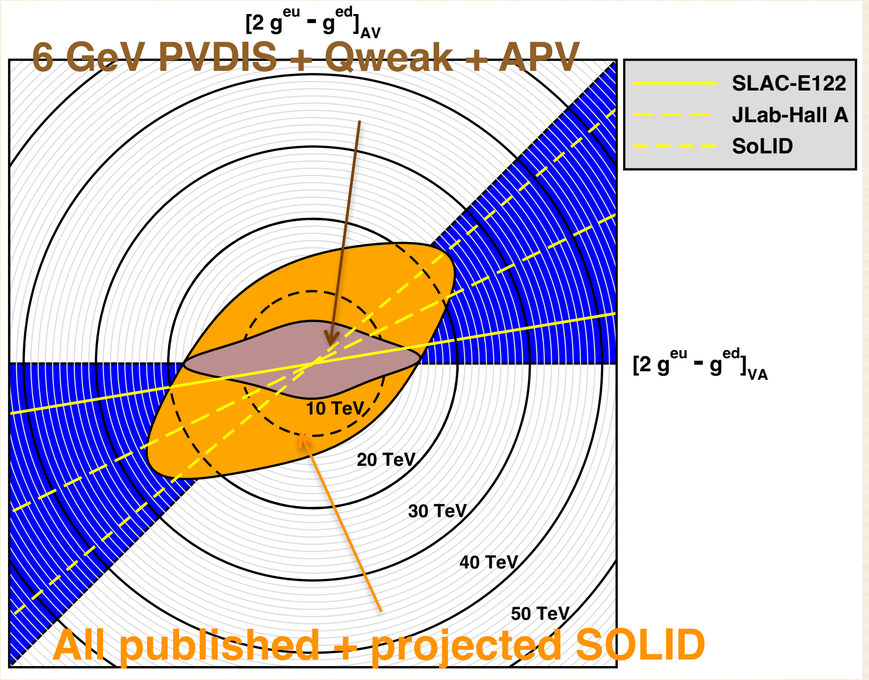
- *High Luminosity with E > 10 GeV*
- *Large scattering angles (for high x & y)*
- *Better than 1% errors for small bins*
- *x-range 0.25-0.75*
- *W^2 > 4 GeV^2*
- *Q^2 range a factor of 2 for each x*
  - (Except at very high x)
- *Moderate running times*



SoLID New Physics Sensitivity

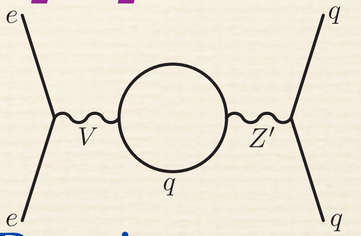


Courtesy: J. Erler

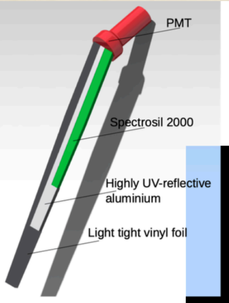


Qweak, P2 and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

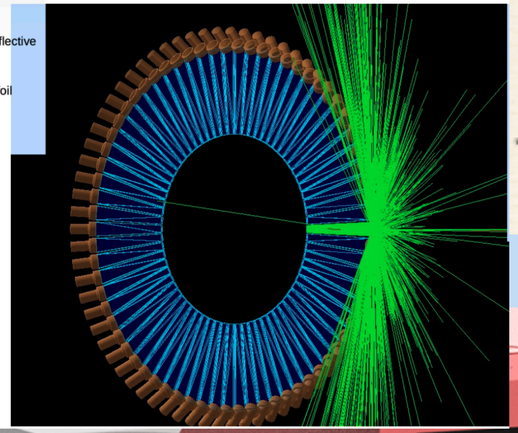
Leptophobic Z'



SOLID can improve sensitivity: 100-200 GeV range

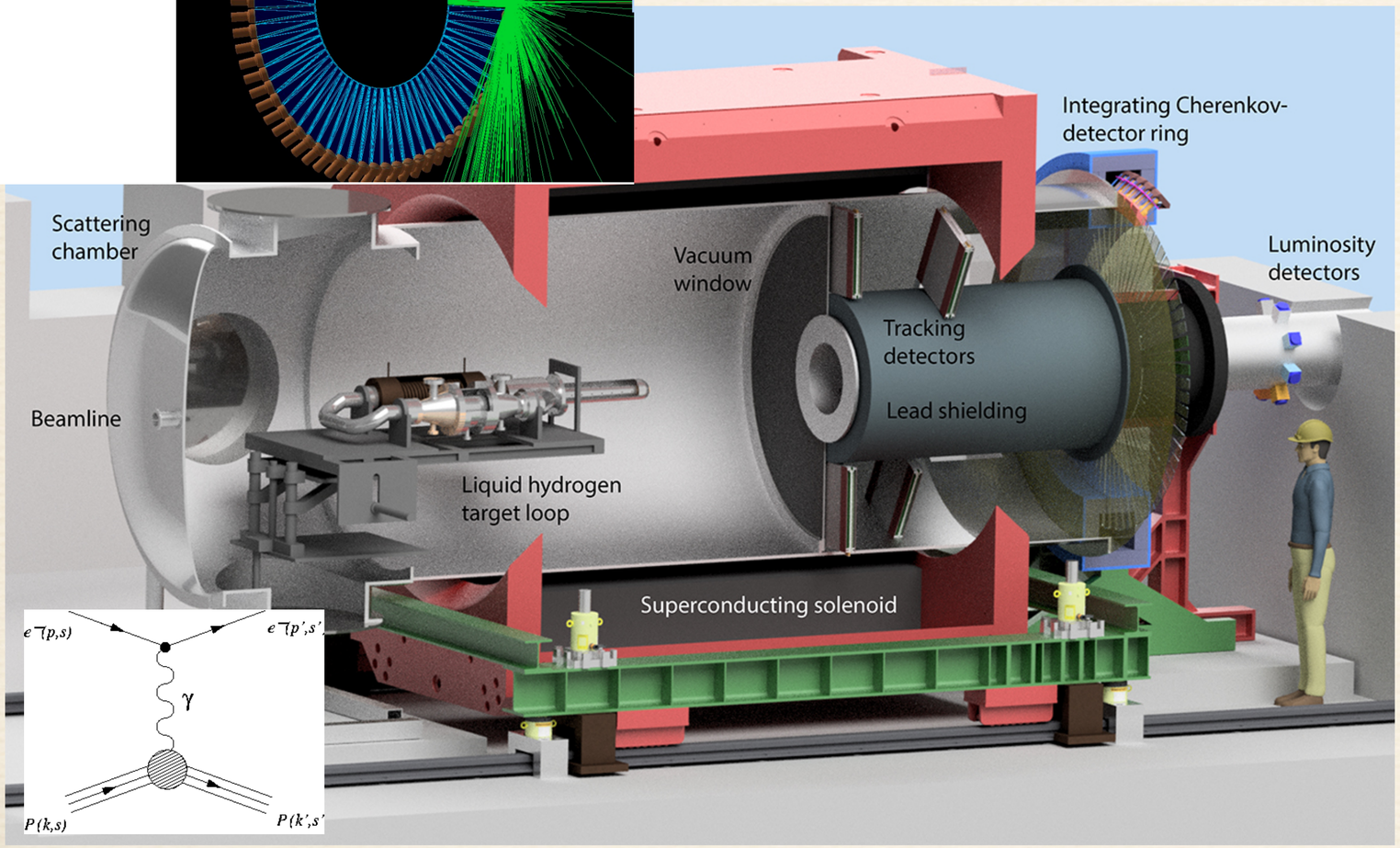


Radiation Hard
Fused Silica
Cherenkov detectors



$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[\,Q^2\,Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

P2 at MESA



60 cm LH2 target 155 MeV, 150 μA 90% beam polarization

P2@MESA hydrogen	P2@MESA carbon
A_{ep}=-28 ppb	A_{ep}= 416.3 ppb
ΔA_{ep}= 0.5 ppb ppb=1/√N Factor 19 After 11,000 h	ΔA_{ep}^{stat}= 2.7 ppb after 300 h ΔA_{ep}^{stat}= 0.9 ppb after 2500 h
$\Delta A_{ep}/A_{ep}$= 1.8 %	$\Delta A_{ep}/A_{ep}^{stat}$= 0.6 % (0.2 %) Polarimetry!
$\Delta\sin^2\theta_W/\sin^2\theta_W$= 0.15 %	$\Delta\sin^2\theta_W/\sin^2$ θ_W= 0.6 %
Aux. measurem. backward angle	Aux. measurem. backward angle

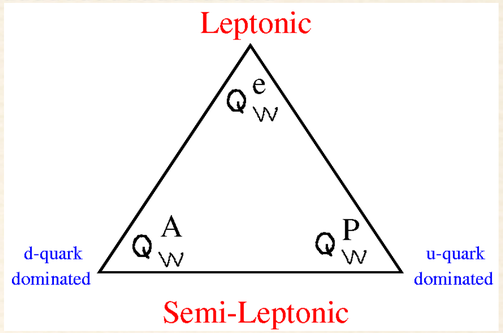
Physics Program 2027 onwards with proton, ^{12}C and ^{208}Pb targets

PVES New Physics Reach

Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4\pi$)

	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

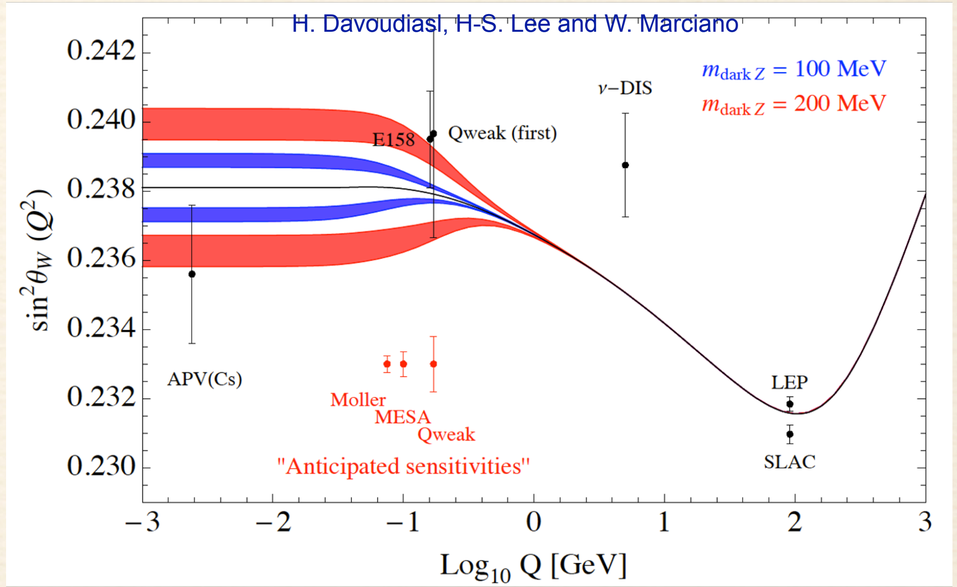
J. Erler



Courtesy: M. Ramsey-Musolf

$$[2C_{2u} - C_{2d}]$$

axial-quark couplings



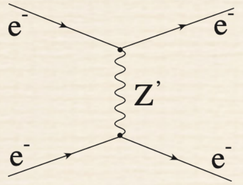
✦Complementary to collider Drell-Yan Searches
✦Unique sensitivity to low energy dark Z's

PVES BSM Search Summary

- **Parity-Violating Electron Scattering was central to the development of the GSW Model of Electroweak Interactions**
- **SLAC E158**
  - ***First precise measurement of the weak mixing angle at low energy***
  - ***Demonstrated the potential of low energy BSM searches in neutral currents***
- **JLab PVES Experiments**
  - ***Pushed technology to new levels of sensitivity***
  - ***Best limits of on new semileptonic neutral current interactions***
- **Future Program**
  - ***MOLLER will begin physics next year, with potential to reach collider sensitivity***
  - ***Two other experiments to push semileptonic neutral current experiments are proposed***

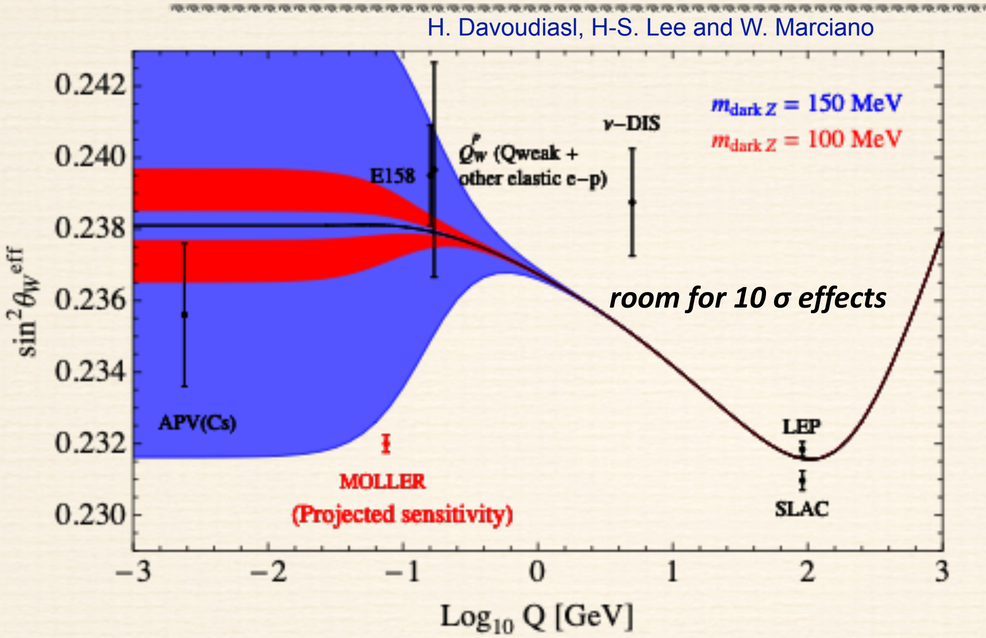
New Physics Examples

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



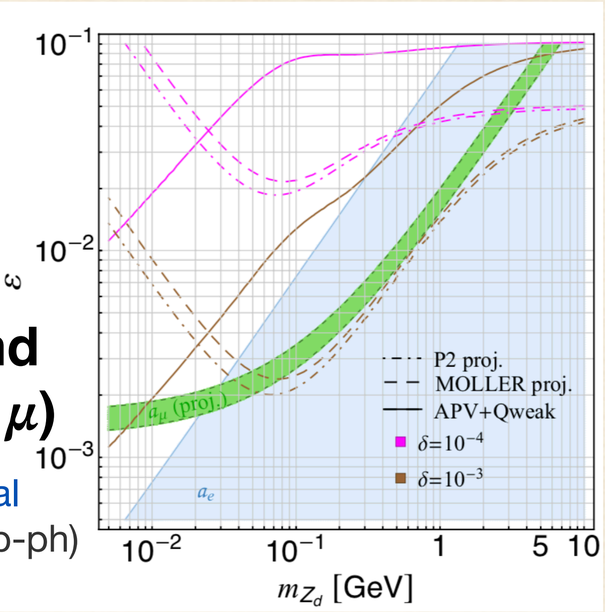
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano



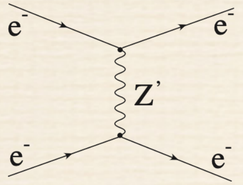
Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al [2104.03280](2104.03280) (hep-ph)



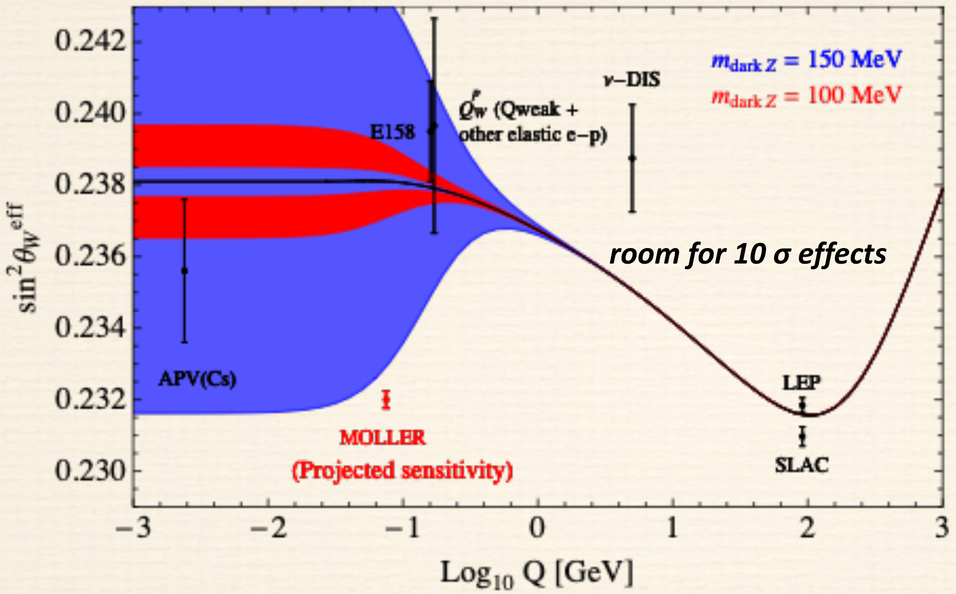
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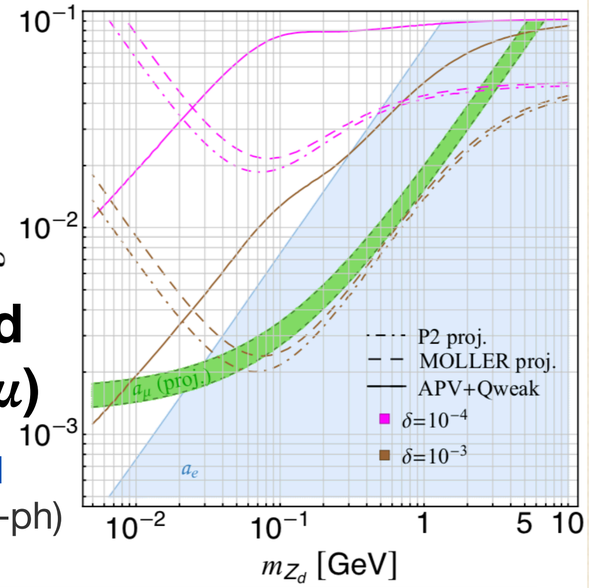
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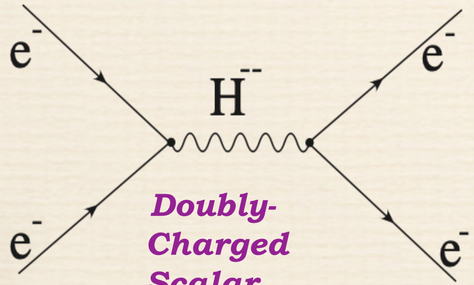


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Lepton Number Violation



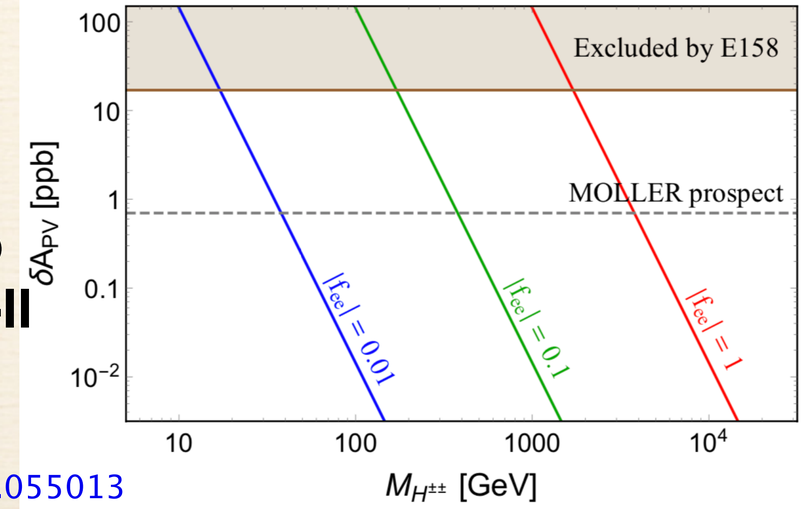
$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\,\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

Cirigliano et al
Phys.Rev. D70 (2004) 075007

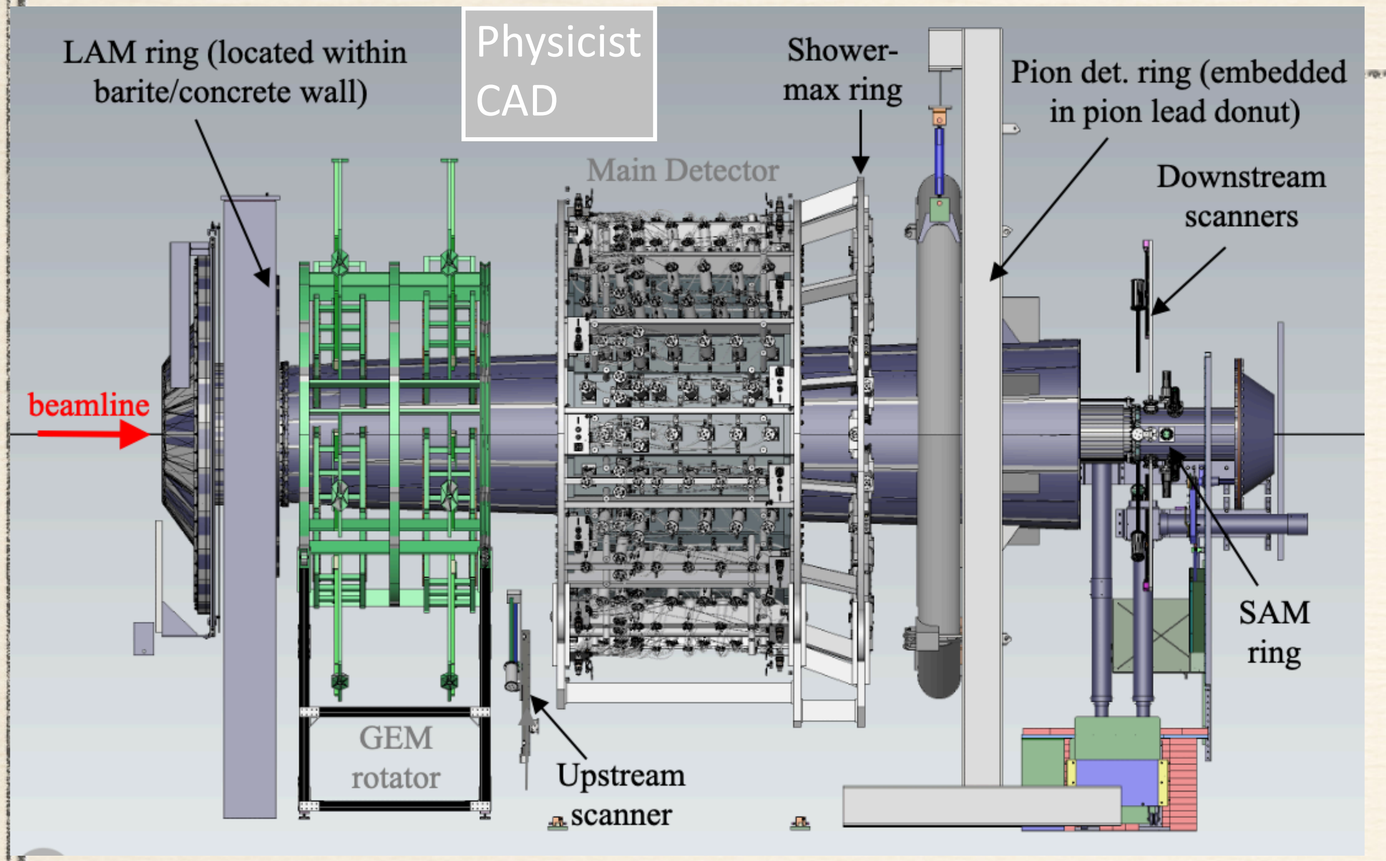
5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

Specific Scenario for Type-II SeeSaw

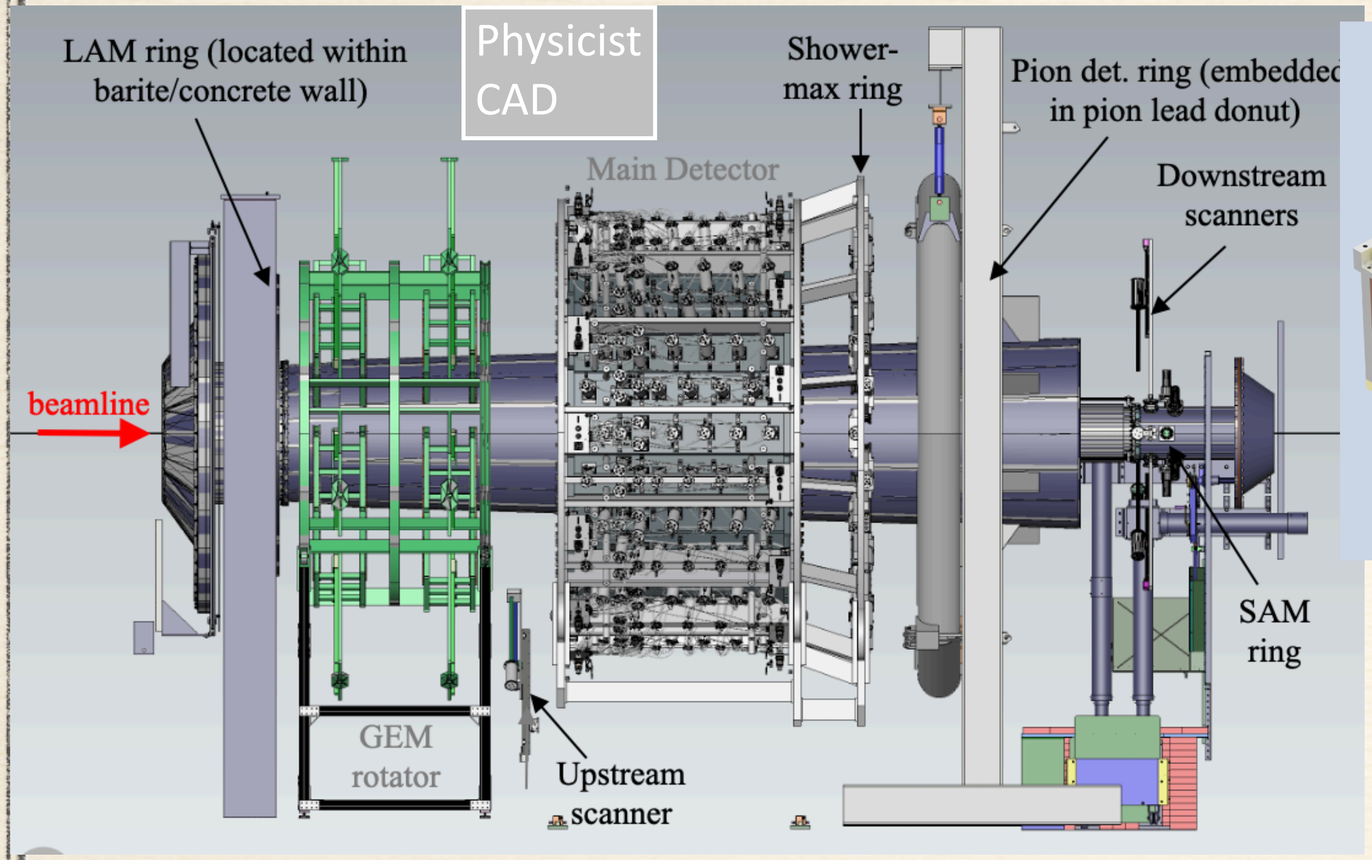
B. Dev et al
PhysRevD.98.055013

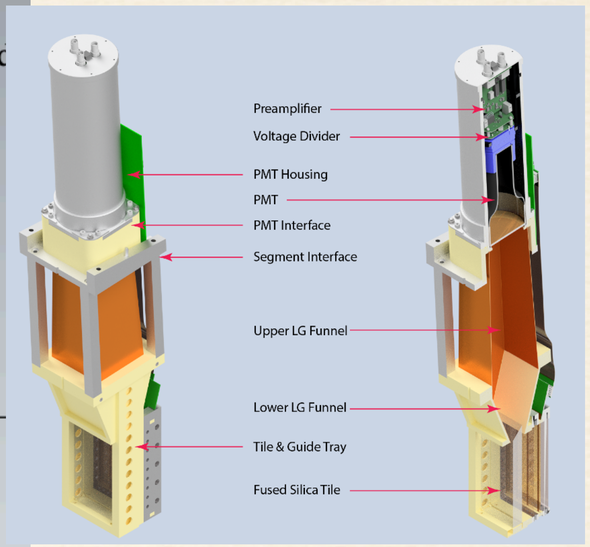


MOLLER Detection Overview



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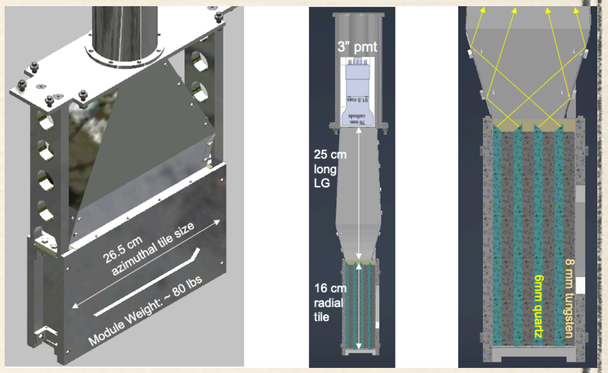




Requirement for Ring 5:

Detector resolution < 25%

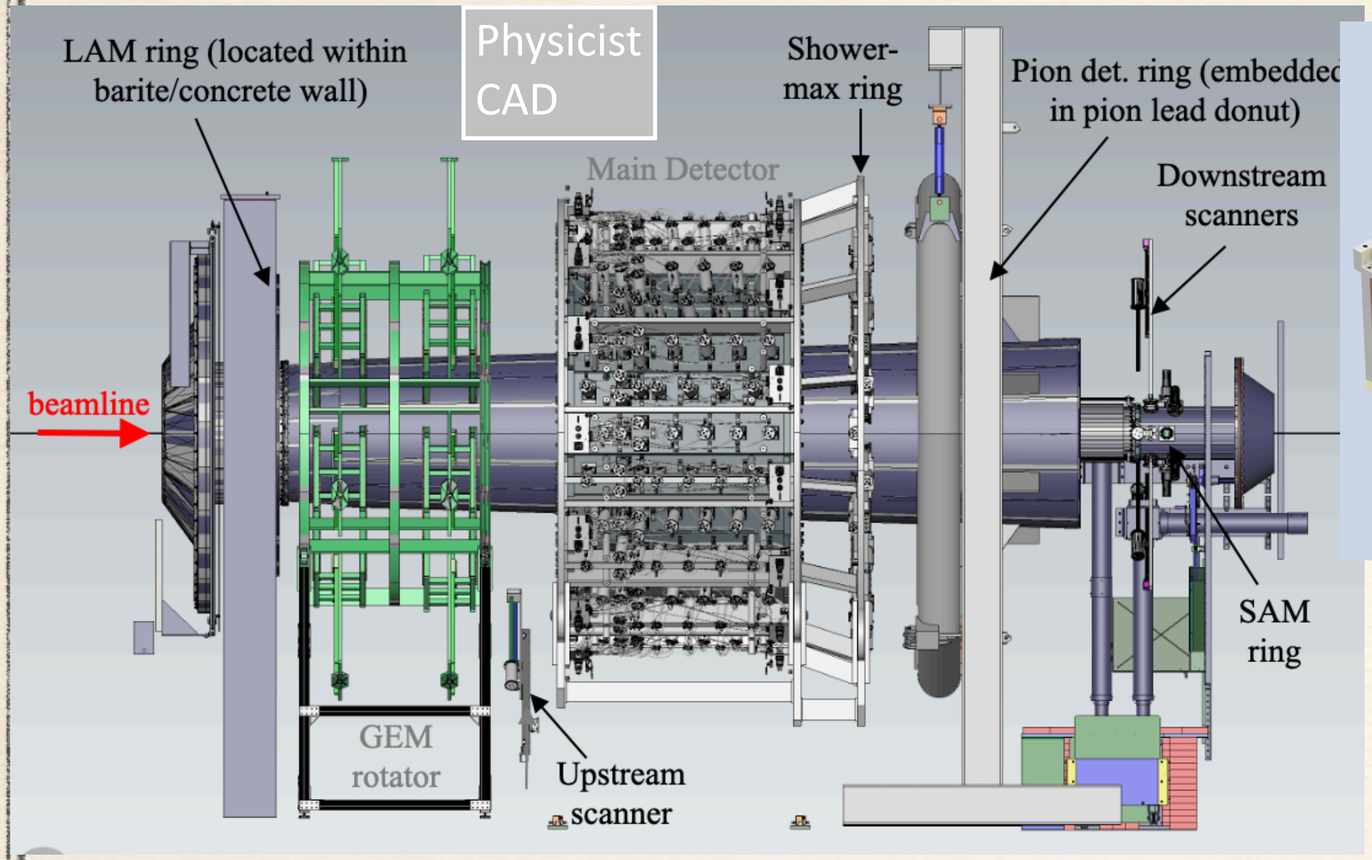
excess noise < 4%

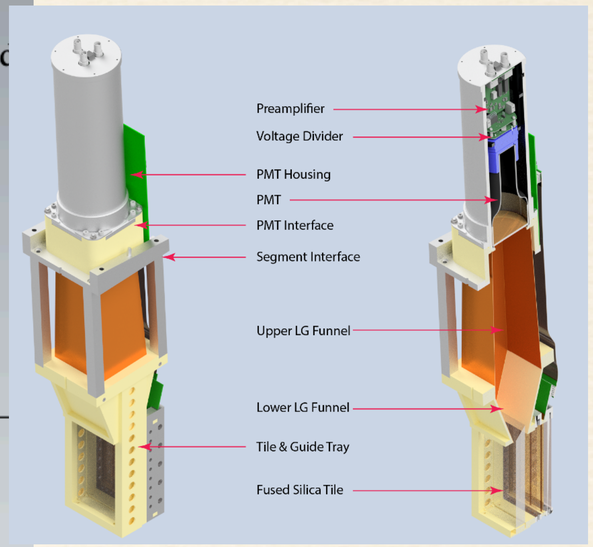


Integrating (current mode) detectors:

asymmetry measurements of both signal and background, and beam and target monitoring

MOLLER Detection Overview

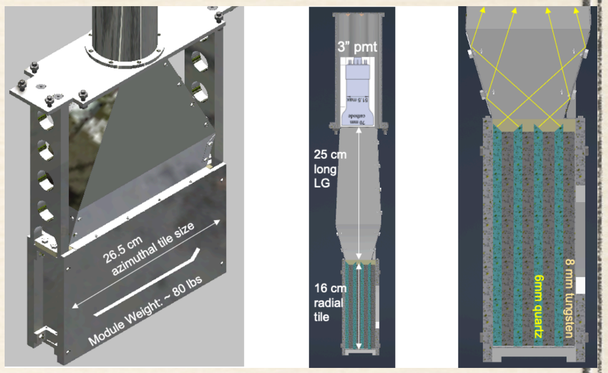




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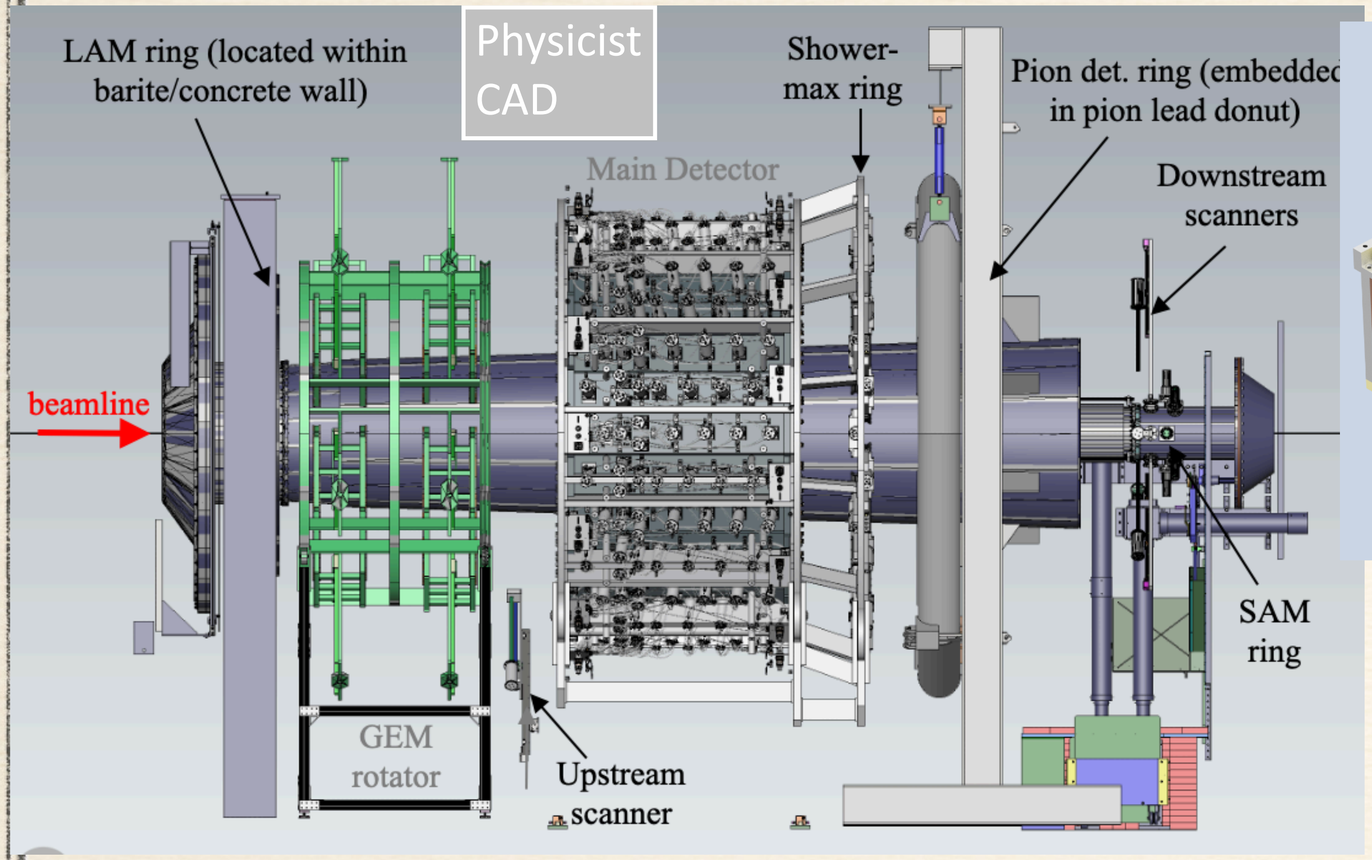
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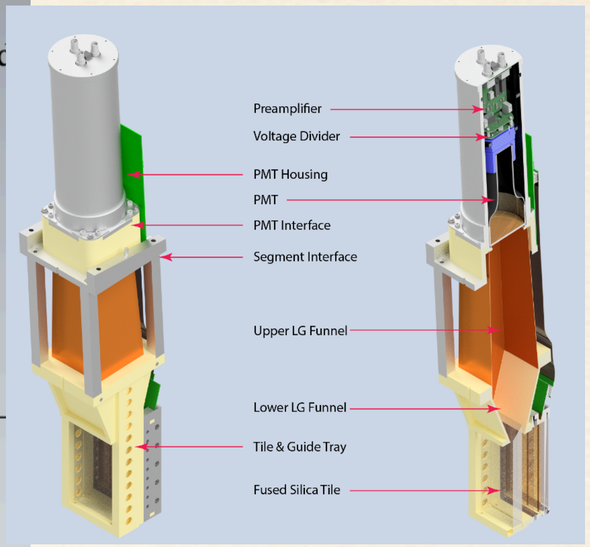
Tracking (counting mode) detectors:

spectrometer calibration, electron scattering angle distribution, and background measurements

- Gas electron multipliers (GEM) detectors
- "Pion" acrylic Cherenkov detectors

MOLLER Detection Overview

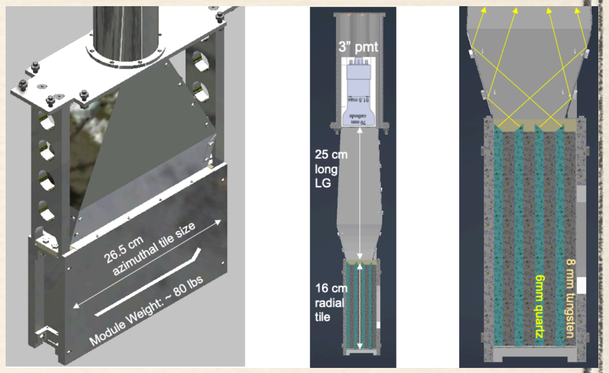




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Readout Electronics:

- Integration mode DAQ & trigger
  - *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  - *input rates between 10~kHz and 300~kHz*