Memories from 50 years of parity violation in electron scattering

Paul Souder

Syracuse University

(Slides from KK and Gordon)

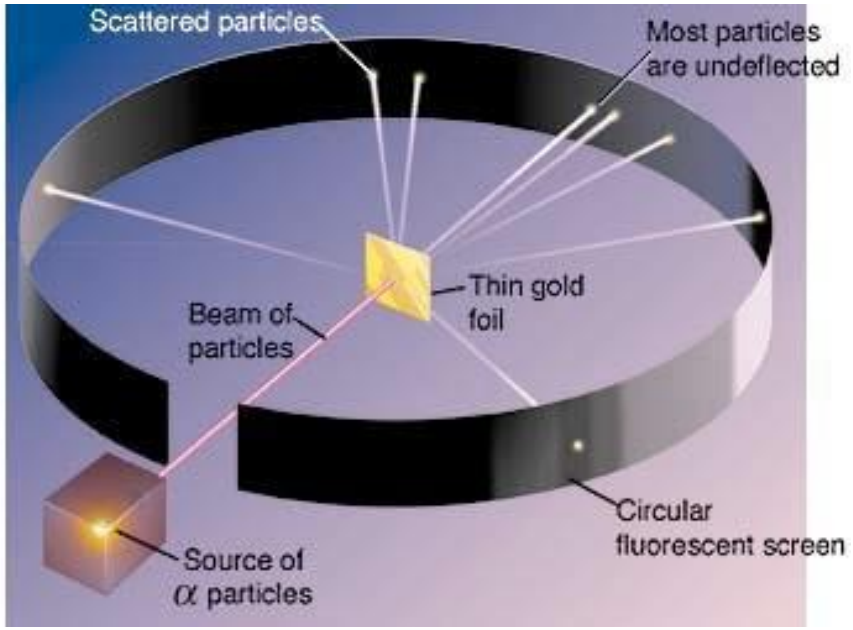
Outline

- Setting the stage
- High energy polarized electrons and PVES
- New directions: 12 C at Bates
- Moller scattering at SLAC

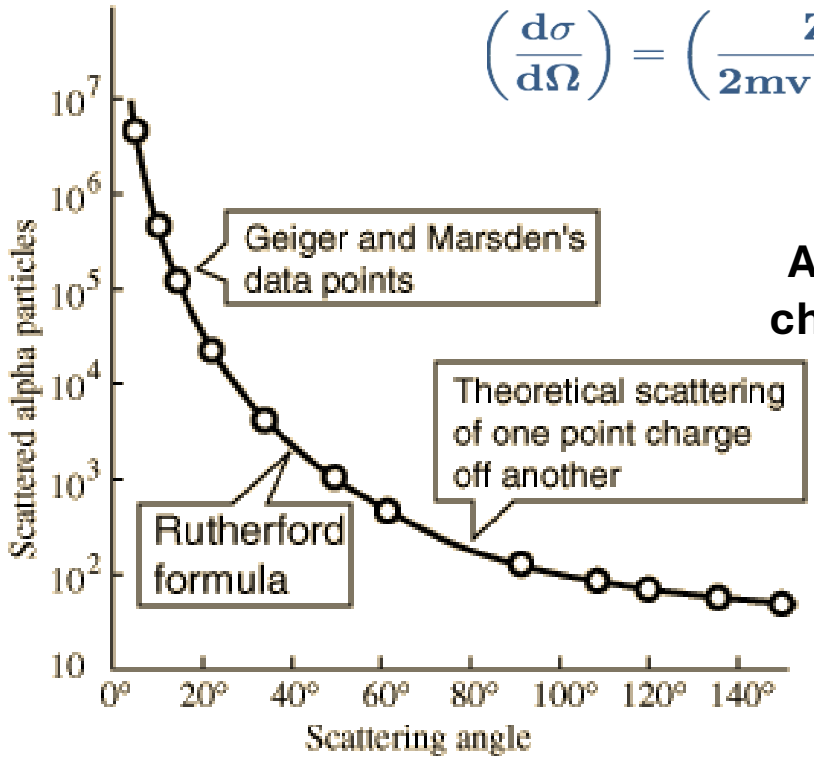
First Fixed Target Experiment

~ 1910s

alpha particles & gold atom's positive charge: interaction governed by Maxwell's equations



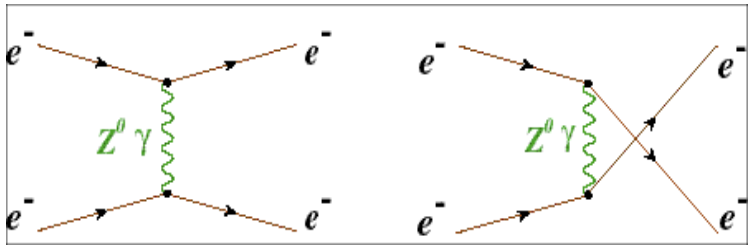
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{Z_1 Z_2 \alpha}{2mv^2 \sin^2(\theta/2)}\right)^2$$



Atom's positive charge: static EM potential

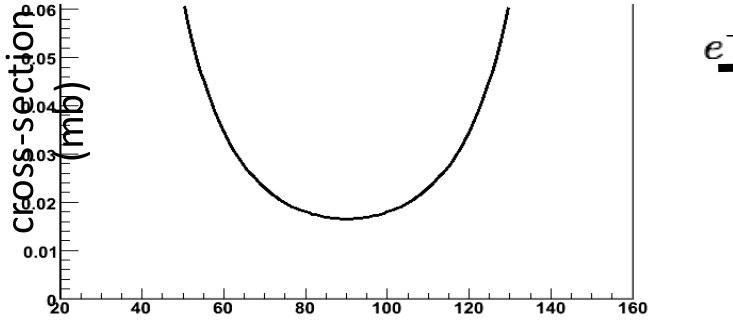
- ***Established that atoms have a tiny nuclear core ~ 10^{-14} m, << atomic size of 10^{-10} m***
- ***Revolutionized experimentation: particle scattering as a microscope***

Moller Scattering: Relativistic QED Theory



~ 1930s

- ***Scattering of identical particles***
- ***Direct and Exchange diagrams***
- ***"Anti-symmetrize" amplitude***

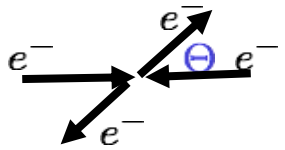


low y — Center of Mass — high y

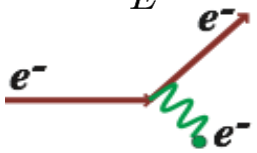
low scattered energy — Angle — high scattered energy

$$E'_{lab} = \frac{E_{beam}}{2}(1 + \cos\theta)$$

center of mass frame



$$y \equiv 1 - \frac{E'}{E}$$



fixed target frame

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2mE}\frac{(3+\cos^2\theta)^2}{\sin^4\theta}$$

$$= \frac{\alpha^2}{4mE}\frac{1+y^4+(1-y)^4}{y^2(1-y)^2}$$

$$\sqrt{s} = \sqrt{2m_e E_{beam}}$$

First Collider Experiment

~ 1960s

A TEST OF QUANTUM ELECTRODYNAMICS BY ELECTRON-ELECTRON SCATTERING*

W. C. Barber†, B. Gittelman‡, G. K. O'Neill‡, and B. Richter**

Stanford University

- **A group at SLAC was developing the concept of an electron storage ring (led to the first e^+e^- collider in the early 1970s)**
- **The group measured differential cross-section as a function of angle; included higher orders in perturbative expansion**

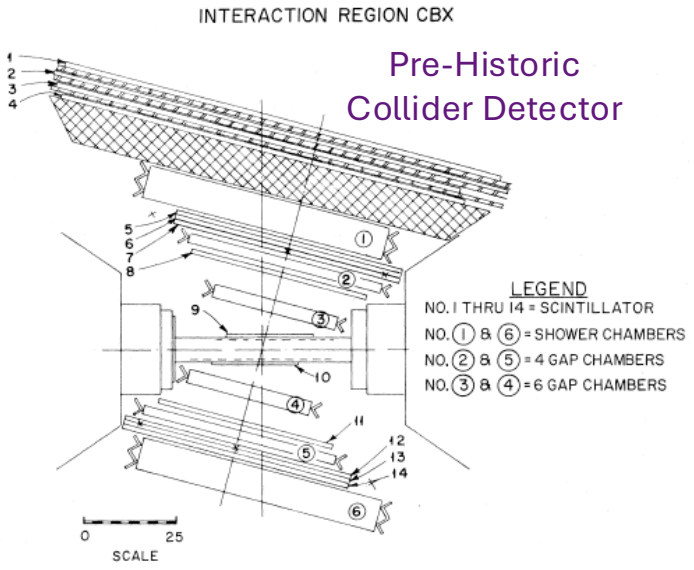
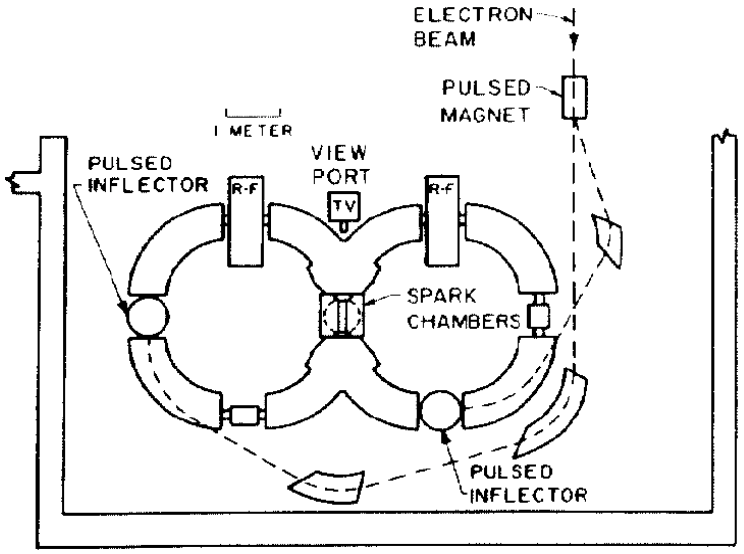


FIG. 1. Storage-ring interaction region and detector system for 556-MeV/electron scattering experiment.

Pre-Historic Collider Detector



"Figure 8" Storage Ring Pair on Stanford University Campus

Tested QED at the 10^{-15} m scale

Technical advancement for a parallel goal: (build colliders to find new particles)

Physics topic (test QED at short length scales) justified R&D activity

Birth of e^+e^- collider physics

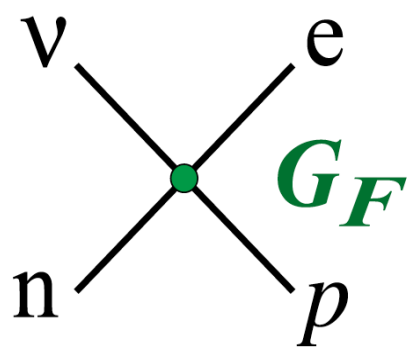
Add Weak Interactions





Fermi Theory for weak interactions

Universal strength: coupling constant G_F



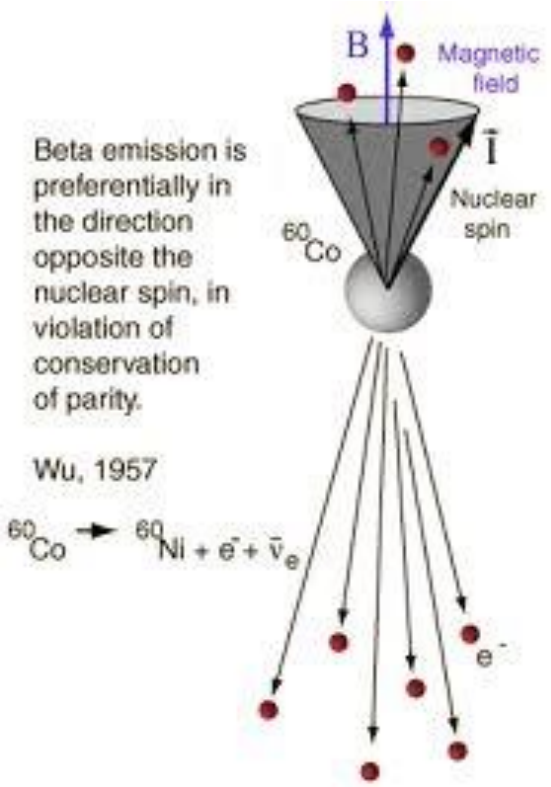
"Effective" low energy theory that explains many observed properties of radioactive nuclear decays

Theory known to breakdown at energy > 100 GeV

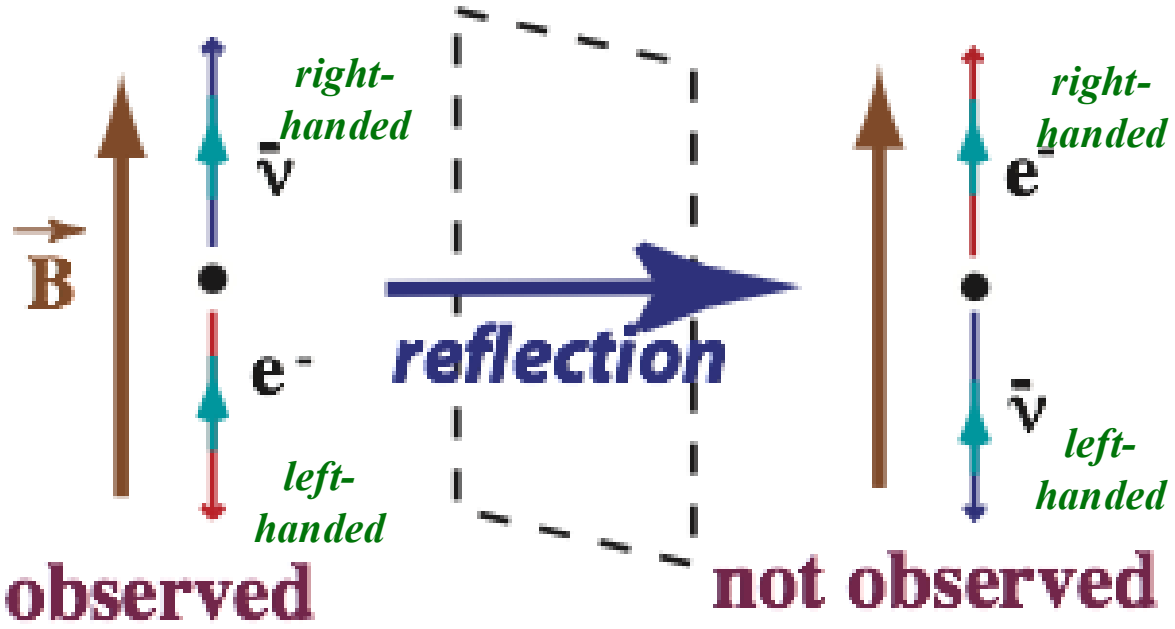
Experimental Verifying of Parity Violation in Weak Interactions

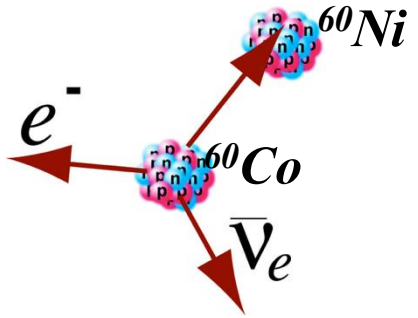
parity transformation (reflection)

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



Only p flips with reflection



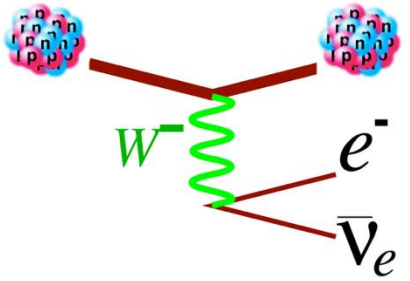


Weak decay of ^{60}Co Nucleus

1958

I was 14 years old, and unaware of the work

First PVES Paper



left-handed electron

right-handed anti-neutrino

Mirror reflection flips sign of helicity

matter particles have spin = 1/2

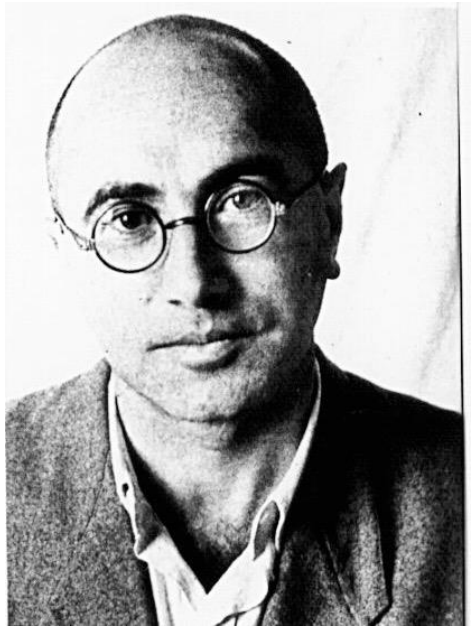
Left-handed ⟺ *right*-handed

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

handedness or ***helicity/chirality***

Only left-handed particles can exchange W bosons

What I learned in grad school (1966): There are no neutral weak currents



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)

Suggested that Weak Current Exists and Violates Parity

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

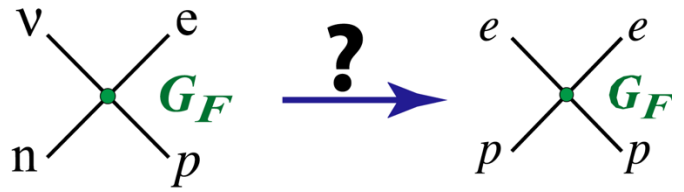
$$g\,(\bar{P}OP)\,(\bar{e}^{-}Oe^{-}) \qquad (2)$$

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.

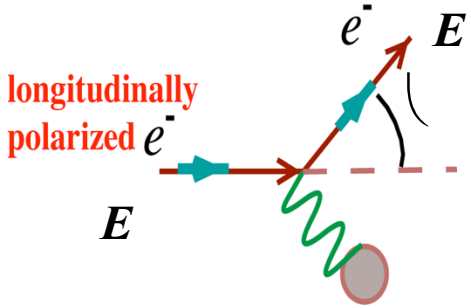
Neutron ® Decay *Electron-proton Weak Scattering*



$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

$$\sim |A_{EM}|^2 + 2A_{EM}A^*_{weak} + \ldots$$

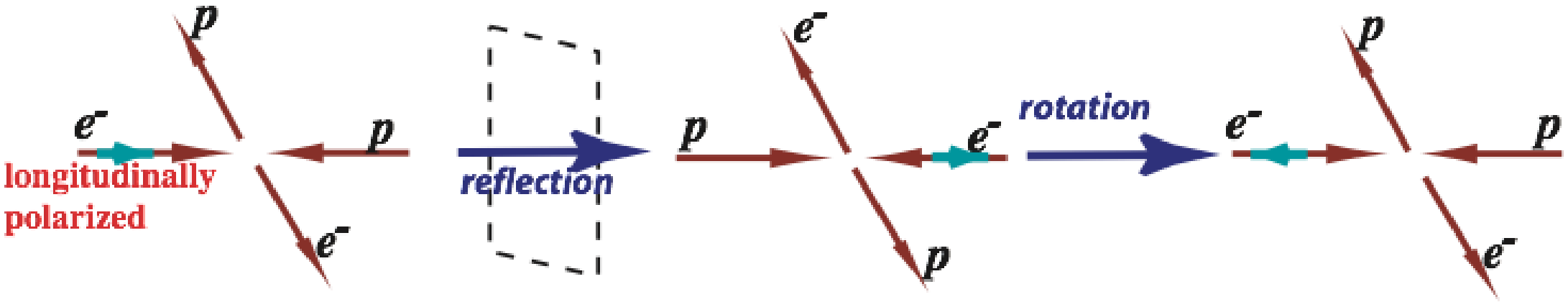
$$A_{PV} = \frac{\sigma_{\uparrow}^{-} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = -A_{LR}$$



4-momentum transfer

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

Parity-Violating Observable



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

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.

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

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

Higgs Mechanism + Renormalizability

Electroweak Unification

$$\tan\theta_W = \frac{g'}{g} \qquad e = g\sin\theta_W$$

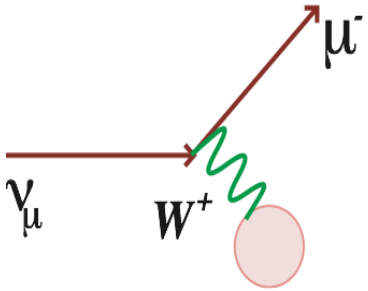
$$\sin^2\theta_W^0 = \left(\frac{e^0}{g^0}\right)^2 = 1 - \left(\frac{M_W^0}{M_Z^0}\right)^2$$

~ 1960s

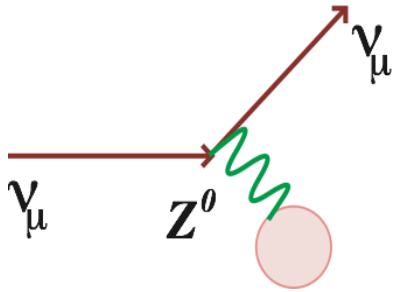
The Z boson incorporated

$$A_\mu = B_\mu^0\cos\theta_W + W_\mu^0\sin\theta_W$$
$$Z_\mu = W_\mu^0\cos\theta_W - B_\mu^0\sin\theta_W.$$

	Left-	**Right-**
©	$0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	zero
Z Charge	$T - q\ sin^2\theta_W$	$-q\ sin^2\theta_W$



Charged Current



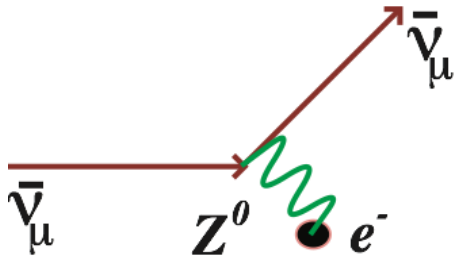
Neutral Current

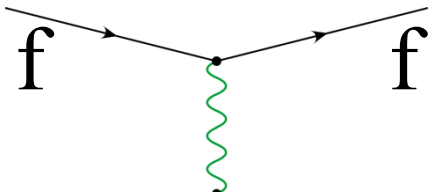
Observation of Weak Neutral Currents



First weak neutral current event:
Gargamelle bubble chamber

~ 1970s





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

My knowledge from grad school became obsolete!

Do Weak Neutral Currents Violate Parity?

Standard Model ruled out by two APV experiments!

Sandars visited us at Yale:
told fun stories about Stephen Hawking

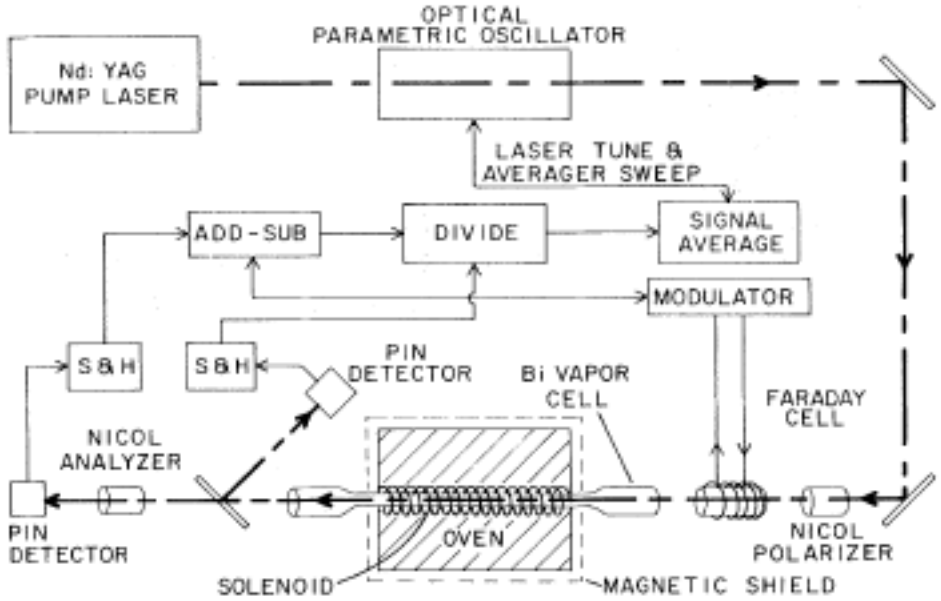


FIG. 1. Schematic view of the apparatus.

Search for Parity-Nonconserving Optical Rotation in Atomic Bismuth

P. E. G. Baird, M. W. S. M. Brimicombe, R. G. Hunt, G. J. Roberts,
P. G. H. Sandars, and D. N. Stacey
Clarendon Laboratory, University of Oxford, Oxford, England
(Received 7 July 1977)

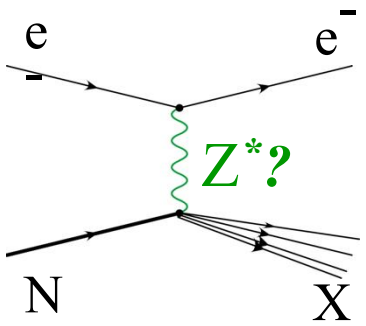
We report the results of a laser experiment to search for the parity-nonconserving optical rotation in atomic bismuth. We work at wavelengths close to the 648-nm $J = 3/2 \rightarrow J = 5/2\, M_1$ transition from the ground state. We find $R = \mathrm{Im}(E_1/M_1) = (+2.7 \pm 4.7) \times 10^{-8}$, in disagreement with the theoretical value $R = -30 \times 10^{-8}$ predicted for this transition on the basis of the Weinberg-Salam model of the weak interactions combined with relativistic central-field atomic theory.

Upper Limit on Parity-Nonconserving Optical Rotation in Atomic Bismuth

L. L. Lewis, J. H. Hollister, D. C. Soreide, E. G. Lindahl, and E. N. Fortson
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 7 July 1977)

We have searched for optical rotation near the 8757-Å magnetic-dipole absorption line in atomic bismuth vapor. The experiment is sensitive to parity nonconservation in the weak neutral-current interaction between electrons and nucleons in atoms. We find $R \equiv \mathrm{Im}(E_1/M_1) = (-0.7 \pm 3.2) \times 10^{-8}$, which is considerably smaller than the value $R = -2.5 \times 10^{-7}$ obtained by central-field calculations for this bismuth line using the Weinberg-Salam theory of neutral currents.

Do Neutral Currents Violate Parity: PVDIS



pressing problem in mid-70's

There were two popular models

$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$ ← *Weinberg model*

Parity is violated

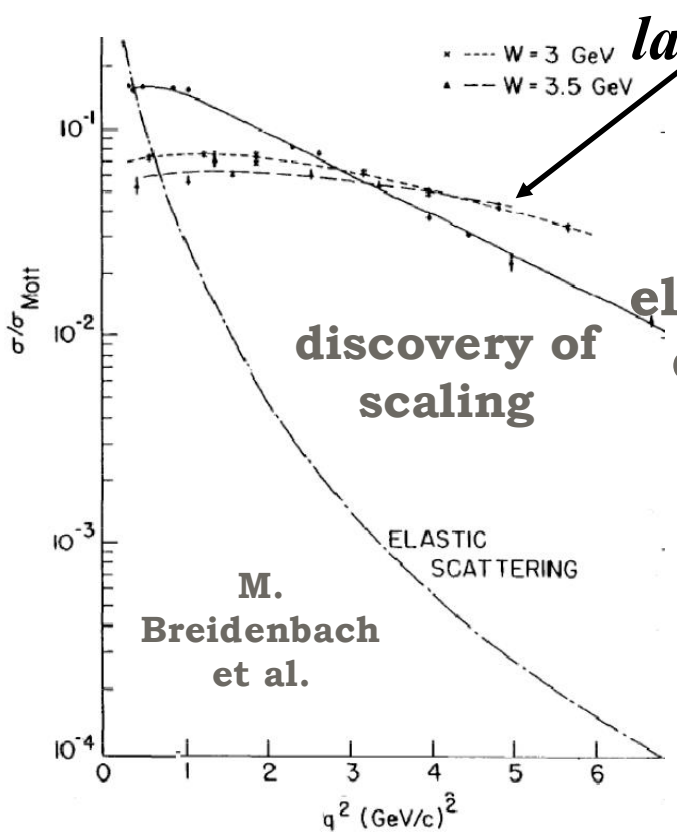
$A_{PV} \sim 10^{-4}$

or

$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^\circ\\ e\end{pmatrix}_r$

Parity is conserved

First table-top atomic parity violation searches: negative!



large rate at large Q^2

discovery of scaling

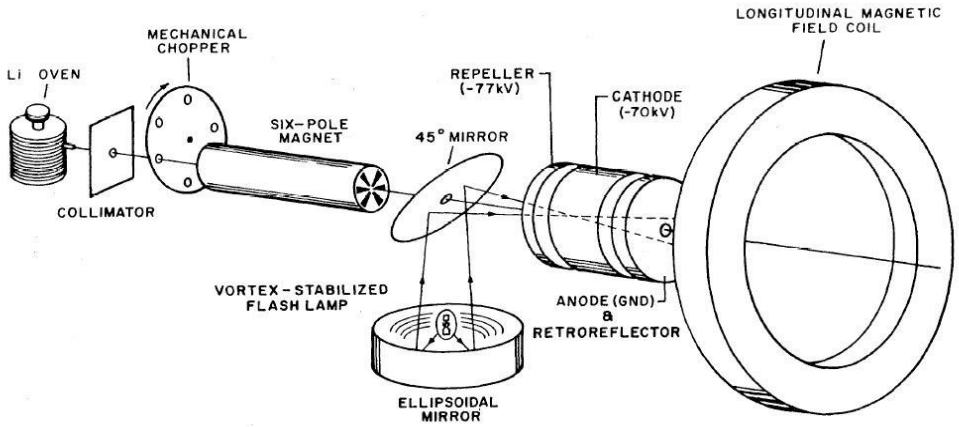
electron-nucleon deep inelastic scattering

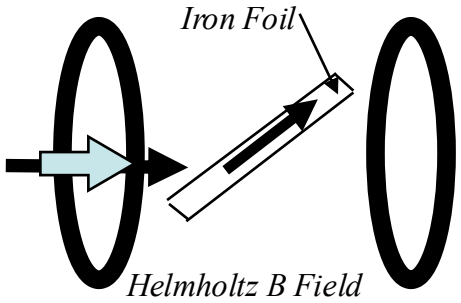
First High-Energy Polarized Electrons

~ 1970s



Vernon W. Hughes





$$\frac{(\sigma_{\uparrow\downarrow} - \sigma_{\downarrow\downarrow})}{(\sigma_{\uparrow\downarrow} + \sigma_{\downarrow\downarrow})} = -\frac{\sin^2\theta(7 + \cos^2\theta)}{(3 + \cos^2\theta)^2}$$

parity-conserving
purely QED effect

POLARIZED ELECTRON-ELECTRON SCATTERING AT GeV ENERGIES*

P.S. Cooper, M.J. Alguard, R.D. Ehrlich, V.W. Hughes,
H. Kobayakawa,† J.S. Ladish,‡ M.S. Lubell, N. Sasao,
K.P. Schüler,‡ and P.A. Souder

J.W. Gibbs Laboratory, Yale University, New Haven, CT. 06520

G. Baum and W. Raith

University of Bielefeld, Bielefeld, West Germany

K. Kondo‖

University of Tokyo, Tokyo, Japan

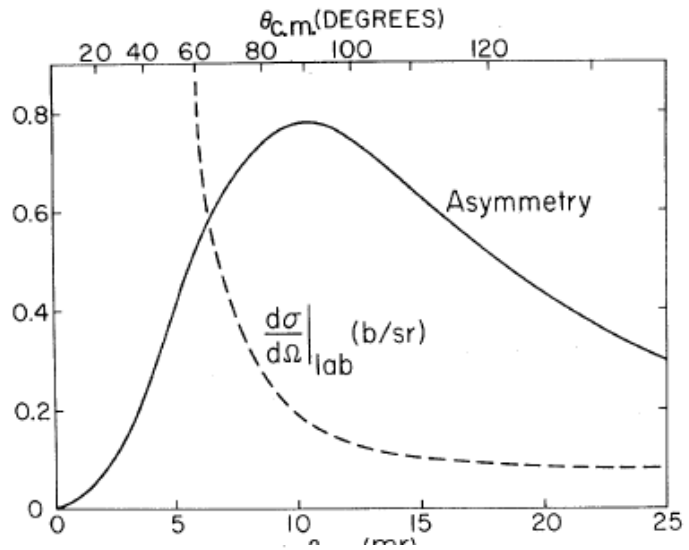
D.H. Coward, R.H. Miller, C.Y. Prescott,
D.J. Sherden, and C.K. Sinclair

Stanford Linear Accelerator Center, Stanford, CA. 94305

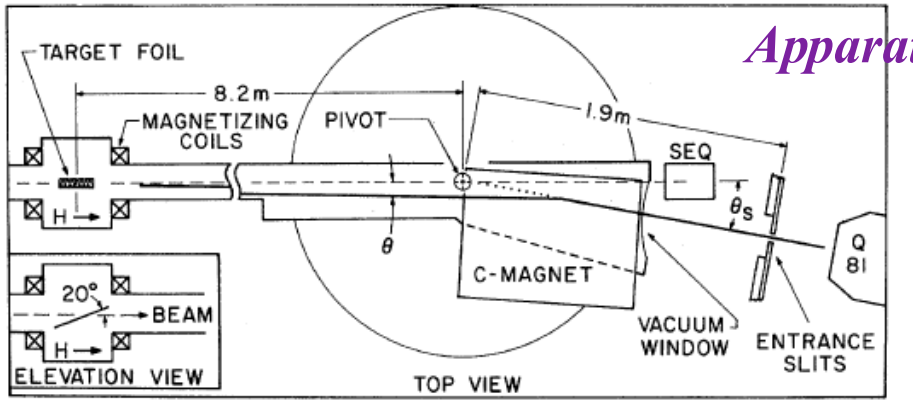
ABSTRACT

The longitudinal polarization of the new Yale-SLAC polarized electron beam has been determined at laboratory energies between 6.47 and 19.40 GeV. Spin-dependent elastic electron-electron scattering (Møller scattering) has been found to be a practical technique for polarization measurements at high energies. The

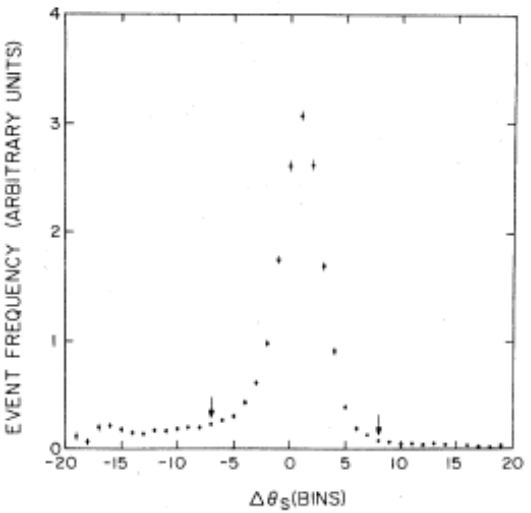
Measurement of Beam Polarization: 76±3%



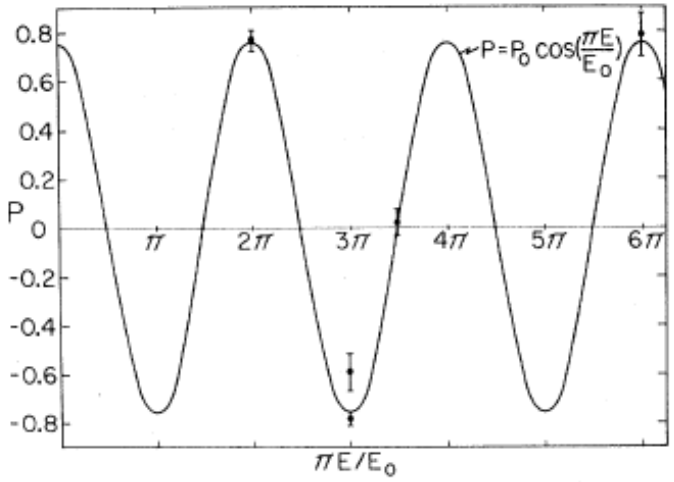
9.7 GeV Kinematics



Apparatus

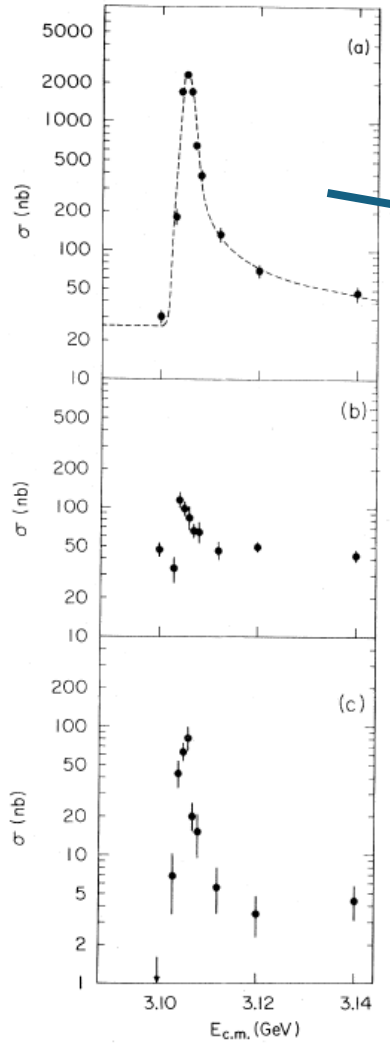


Clean elastic peak



G-2 spin flips

Aside: That Same Weekend...



Announced on the SLAC PA system

Seminar that Monday

Revolution:
Field theory, QCD in
Bootsraps, S-Matrix theory out

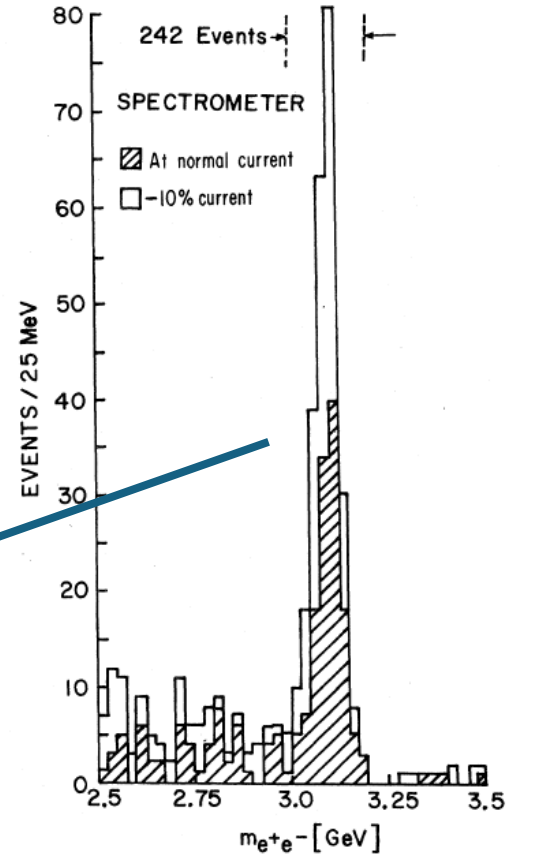


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

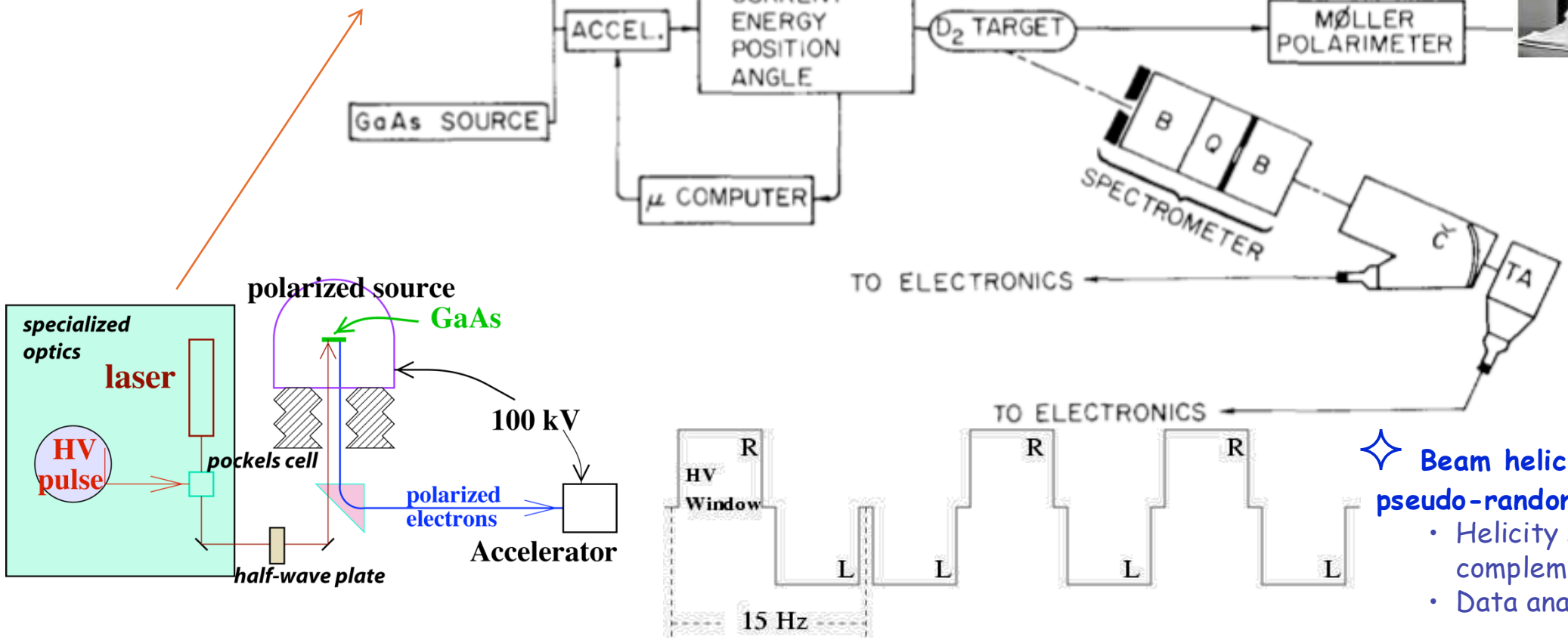
SLAC E122

1978

C.Y. Prescott, *et al.*

Lots of Innioation





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

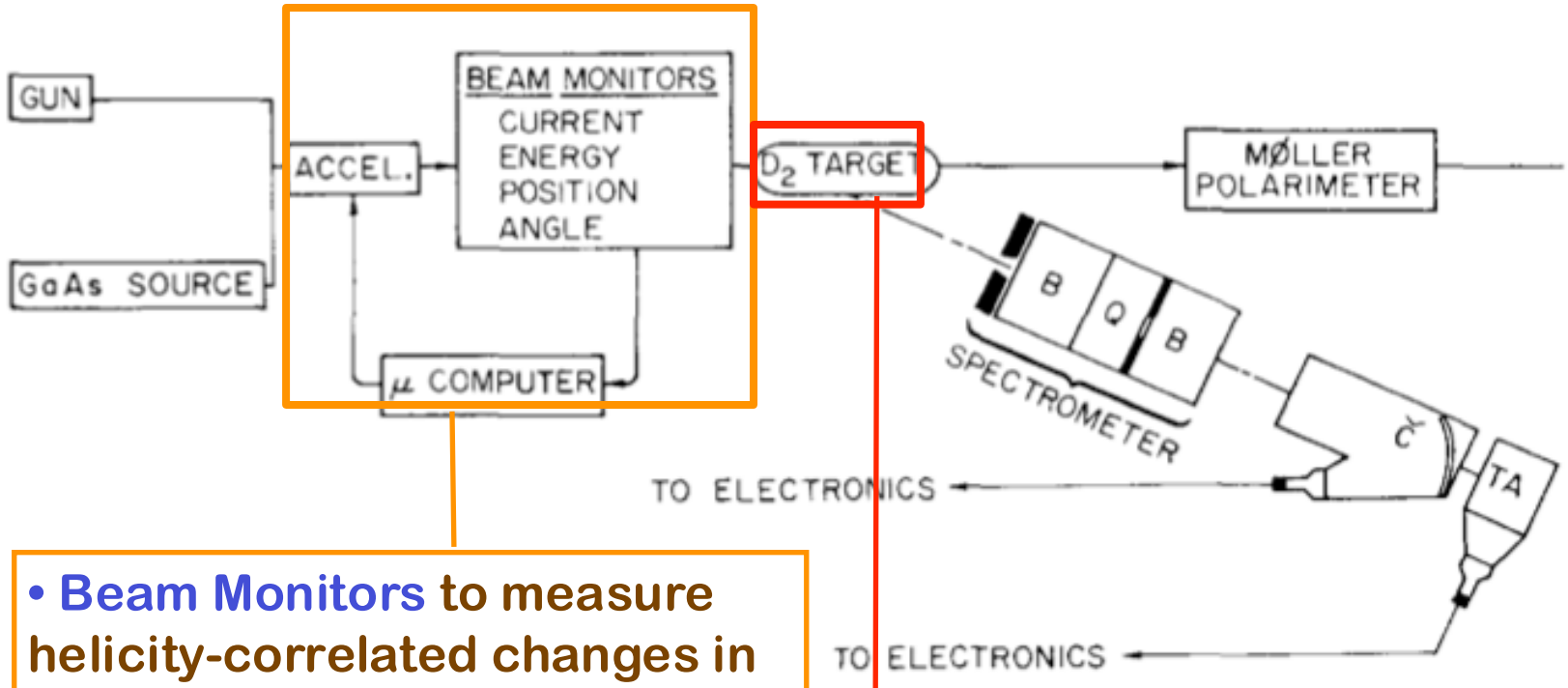
- Helicity state, followed by its complement
- Data analyzed as "pulse-pairs"

SLAC PVDIS: Proposal

A Test of Parity Violation in the Inelastic Scattering of Polarized Electrons at the Level of the Weak Interaction

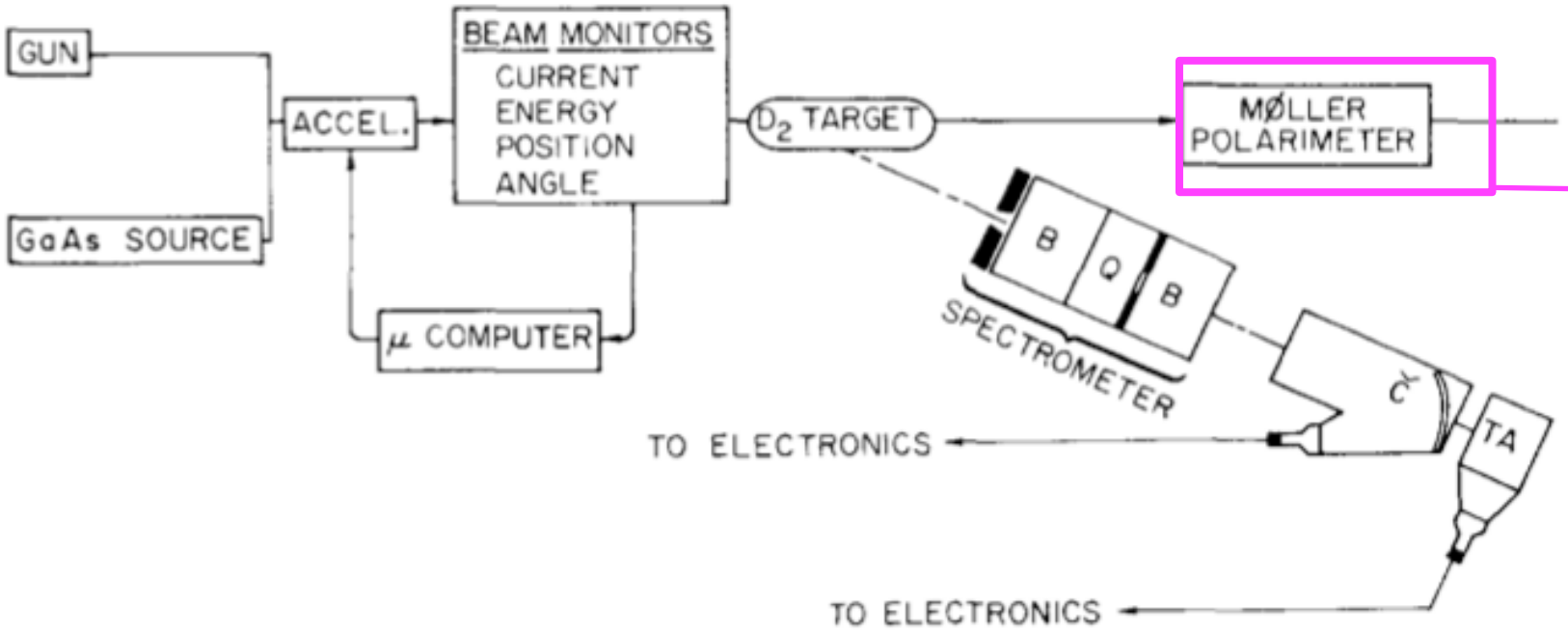
W. Ash(SLAC), W.B. Atwood(SLAC), R.Leslie Cottrell(SLAC), H.C. DeStaebler(SLAC), H. Pessard(SLAC), C.Y. Prescott(SLAC), L.S. Rochester(SLAC), D. Sherden(SLAC), Charles K. Sinclair(SLAC), Richard E. Taylor(SLAC), M.R. Bergstrom(Yale U.), R.D. Ehrlich(Yale U.), V.W. Hughes(Yale U.), M.S. Lubell(Yale U.), K. Kondo(Yale U.), N. Sasao(Yale U.), P.A. Souder(Yale U.), Guenter Baum(Bielefeld U.), W. Raith(Bielefeld U.), K.P. Schuler(Bielefeld U.)

Features: Precision Beam Monitors; Target



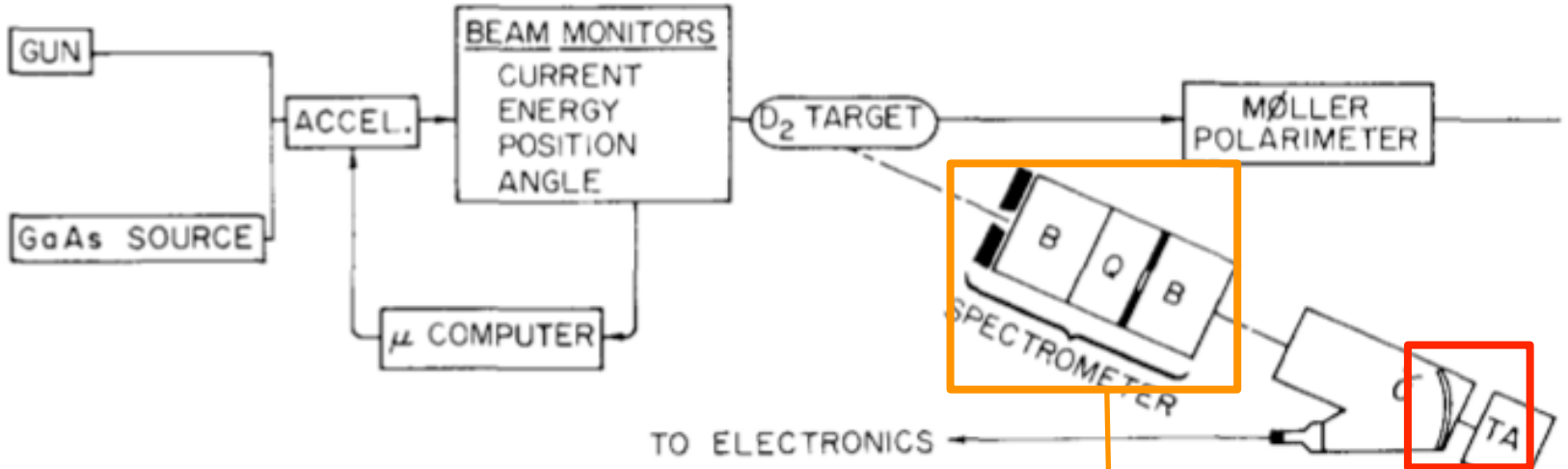
- **Beam Monitors** to measure helicity-correlated changes in beam parameters

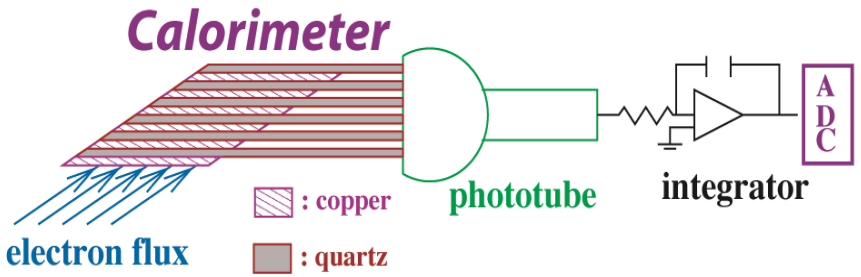
- **High-power cryotarget** 30 cm long for high luminosity



- **Polarimetry**

Novel Flux Integration





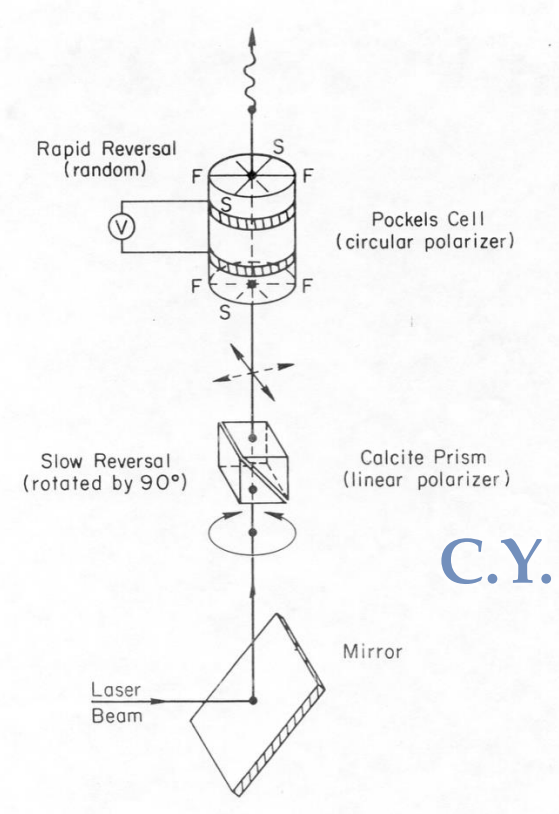
- **Magnetic spectrometer**

directs flux to background-free region

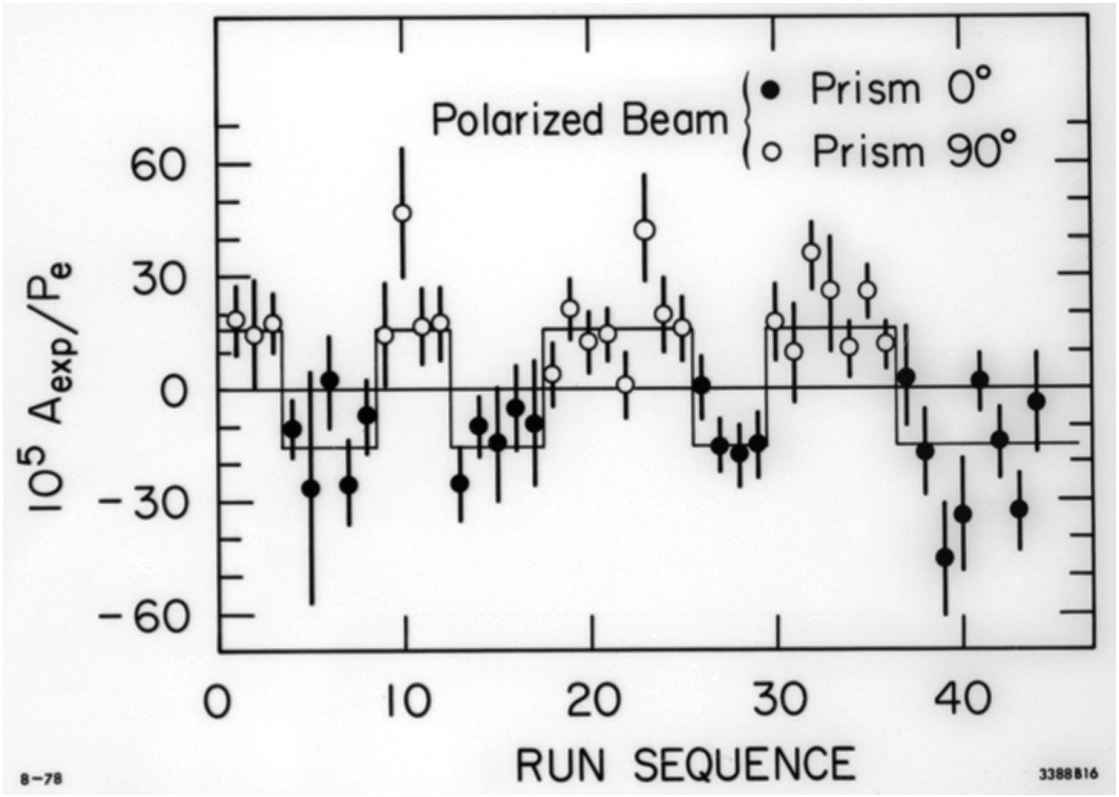
- **Flux Integration**

measures high rate without deadtime

SLAC E122 Results



C.Y. Prescott et al, 1978

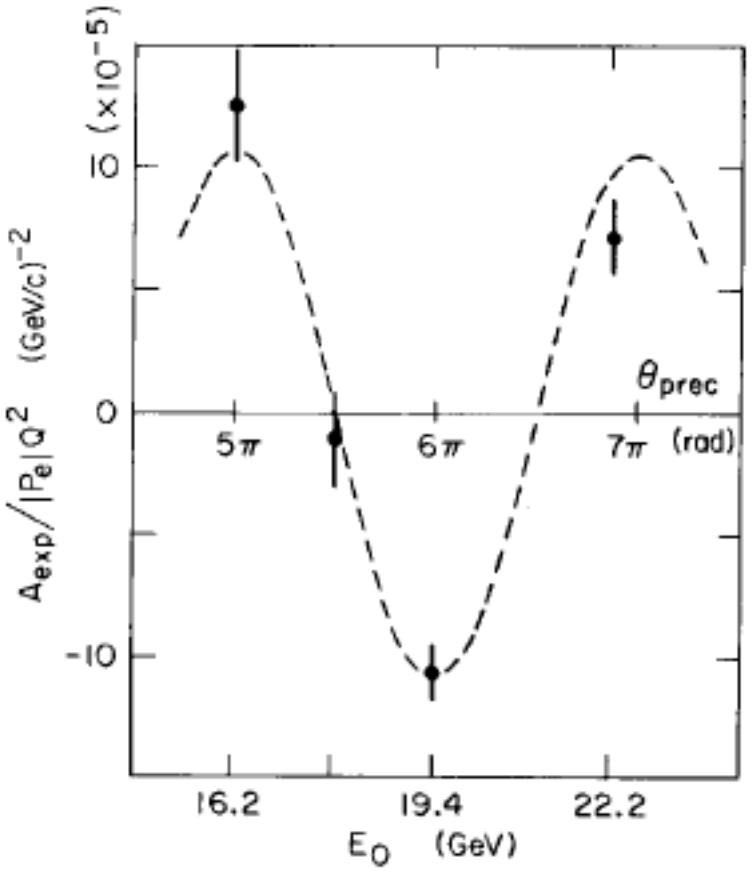


$$A_{PV} \sim 10^{-4} \qquad \delta(A_{PV}) \sim 10^{-5}$$

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

Result Was Convincing!

Lots of statistics
A_{PV} flips with Laser
A_{PV} flips with g-2



Glashow, Weinberg, Salam Nobel Prize awarded in 1979

SLAC PVDIS: Publication

Parity Nonconservation in Inelastic Electron Scattering

C.Y. Prescott(SLAC), W.B. Atwood(SLAC), R.Leslie Cottrell(SLAC), H.C. DeStaebler(SLAC), Edward L. Garwin(SLAC), A. Gonidec(SLAC), Roger H. Miller(SLAC), L.S. Rochester(SLAC), T. Sato(SLAC), D. Sherden(SLAC), Charles K. Sinclair(SLAC), S. Stein(SLAC), Richard E. Taylor(SLAC), J.E. Clendenin(Yale U.), V.W. Hughes(Yale U.), N. Sasao(Yale U.), K.P. Schuler(Yale U.), M. Borghini(CERN), K. Lubelsmeyer(Aachen, Tech. Hochsch), W. Jentschke(Hamburg U.)

What did I do in the meantime?

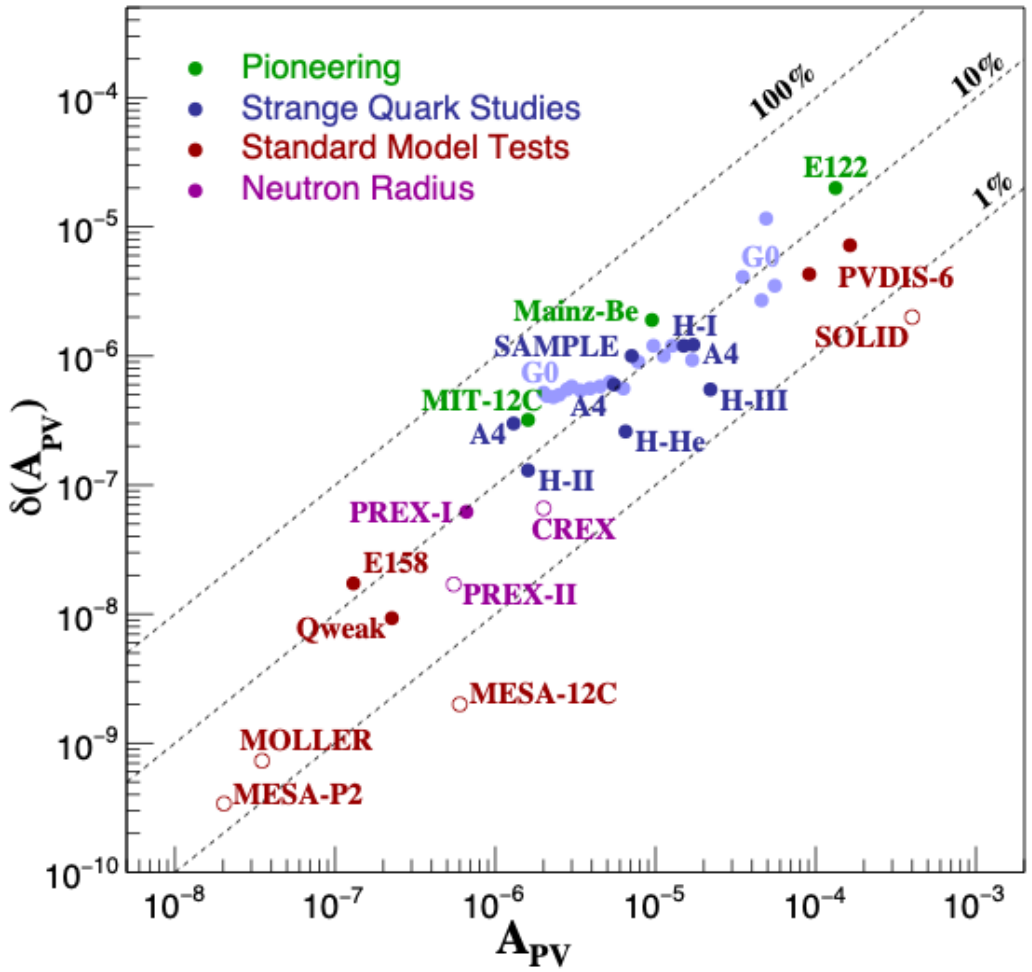
I was intrigued by a talk at a conference that described a proton parity experiment with an unprecedented of precision at the ppm level

I felt that PVES had a bright future if smaller asymmetries (sub-ppm) could be reliable measured with polarized electrons.
Theoretical interpretation would be much cleaner!

So I started with a polarized electron parity experiment at MIT-Bates (1977)

Here is the future that I envisioned (sorta) ~1976

(There were a few details that needed to be worked out)



Improvements in Experimental Techniques:

1. ***High-intensity electron sources***
2. ***High-quality electron beams***
3. ***Precision polarimetry***
4. ***High-power targets***

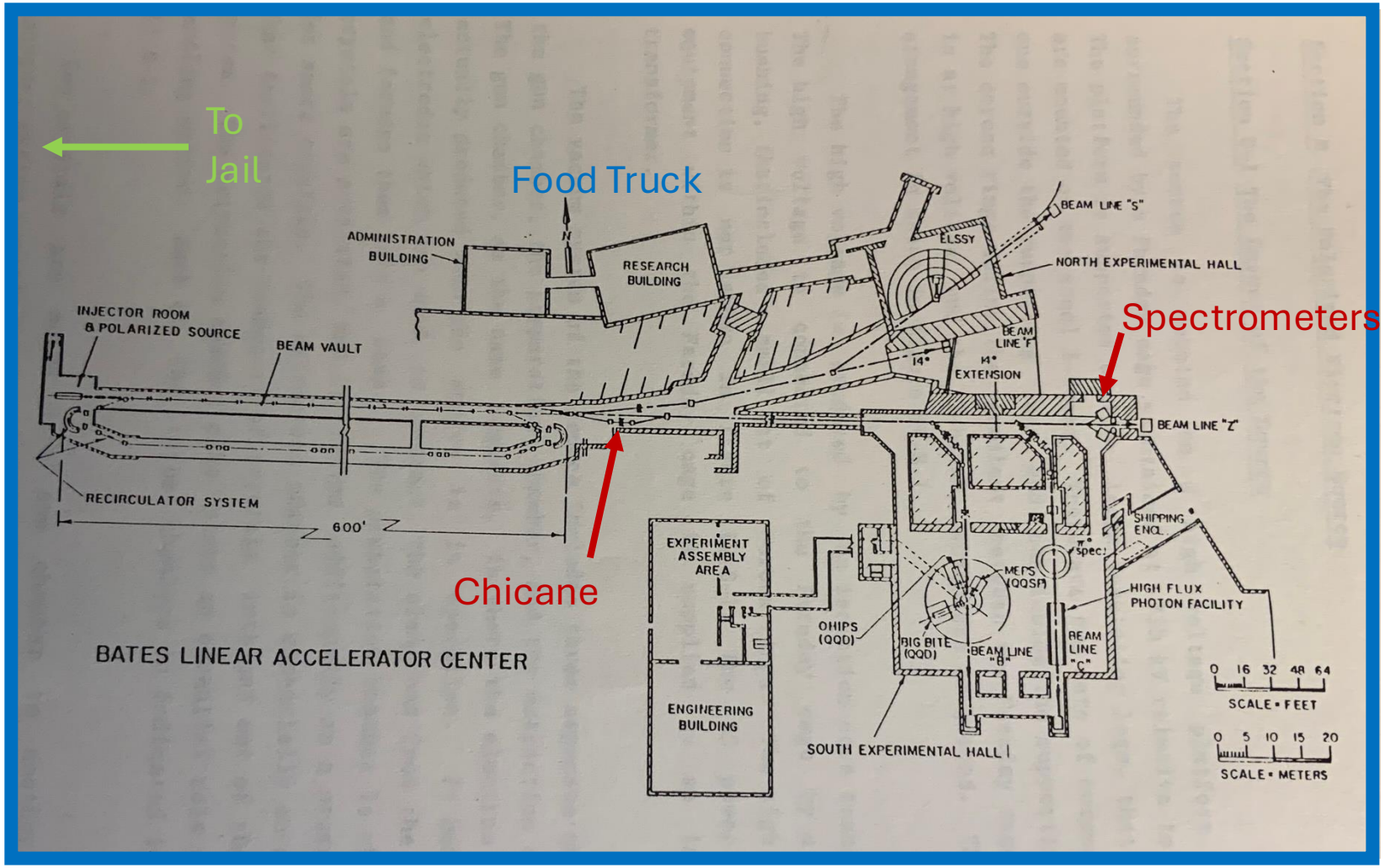
Today, very small asymmetries can be precisely measured

Technical challenges

1. ***How do you detect such tiny effects?***
2. ***How do you measure them at the % level?***

Accelerator at MIT Bates

MIT planned to upgrade this facility. Instead CEBAF was built



Bates ^{12}C Apparatus

1. New GaAs Polarized Source
4. Bates Accelerator
5. Chicane for energy measurement
7. Moller Target
10. 12C target chamber
11. Single quadrupole spectrometer
12. Lucite Cerenkov integrating detectors

Not Shown: Beam dithering apparatus

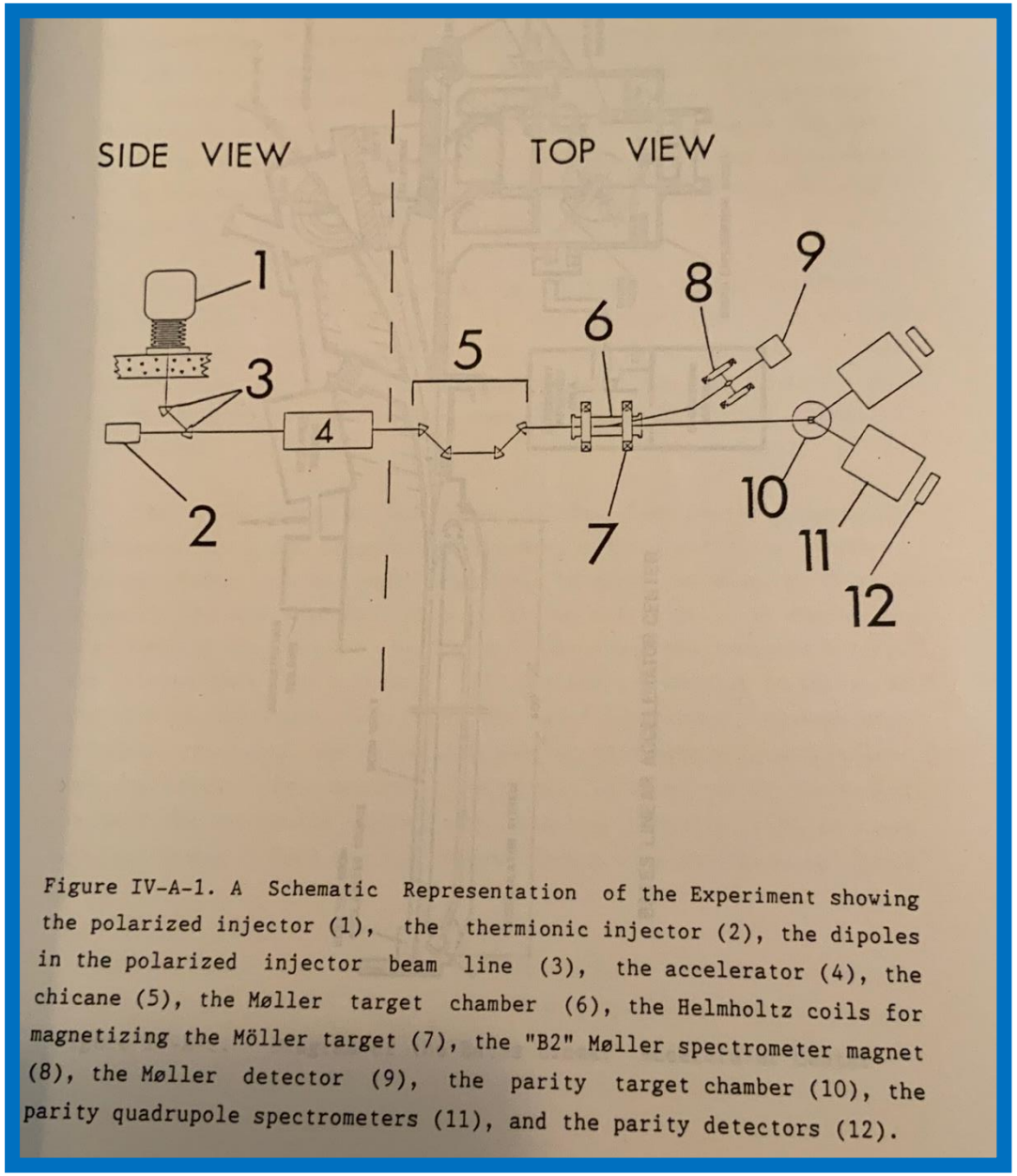


Figure IV-A-1. A Schematic Representation of the Experiment showing the polarized injector (1), the thermionic injector (2), the dipoles in the polarized injector beam line (3), the accelerator (4), the chicane (5), the Møller target chamber (6), the Helmholtz coils for magnetizing the Möller target (7), the "B2" Møller spectrometer magnet (8), the Møller detector (9), the parity target chamber (10), the parity quadrupole spectrometers (11), and the parity detectors (12).

Yale Polarized Electron Source

Built by Gordon Cates

Famous Quote:
“Who is building the Source?

Not Shown:
CW Laser system

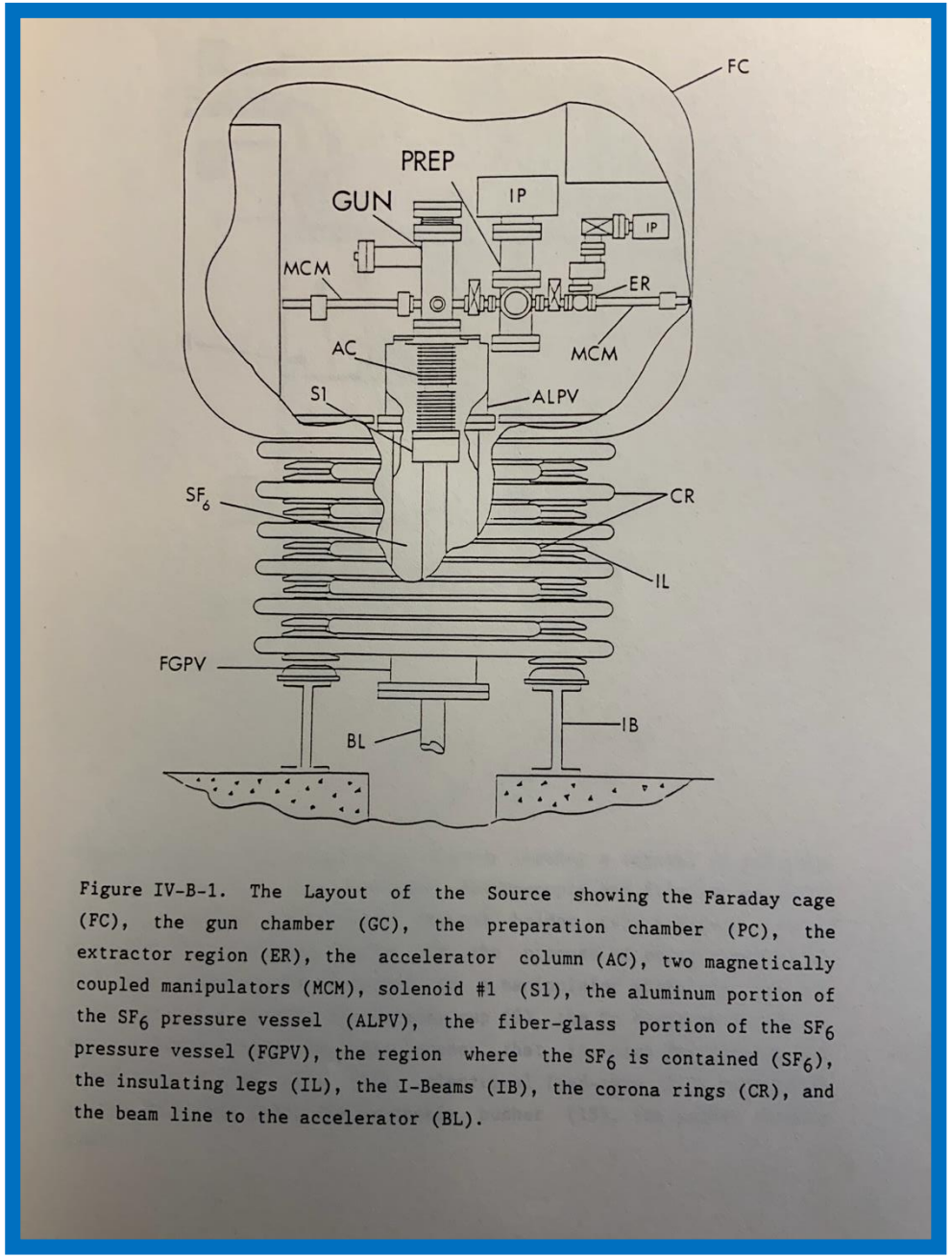


Figure IV-B-1. The Layout of the Source showing the Faraday cage (FC), the gun chamber (GC), the preparation chamber (PC), the extractor region (ER), the accelerator column (AC), two magnetically coupled manipulators (MCM), solenoid #1 (S1), the aluminum portion of the SF_6 pressure vessel (ALPV), the fiber-glass portion of the SF_6 pressure vessel (FGPV), the region where the SF_6 is contained (SF_6), the insulating legs (IL), the I-Beams (IB), the corona rings (CR), and the beam line to the accelerator (BL).

PITA Effect

This was the first use of the PITA effect to eliminate helicity correlated beam intensities

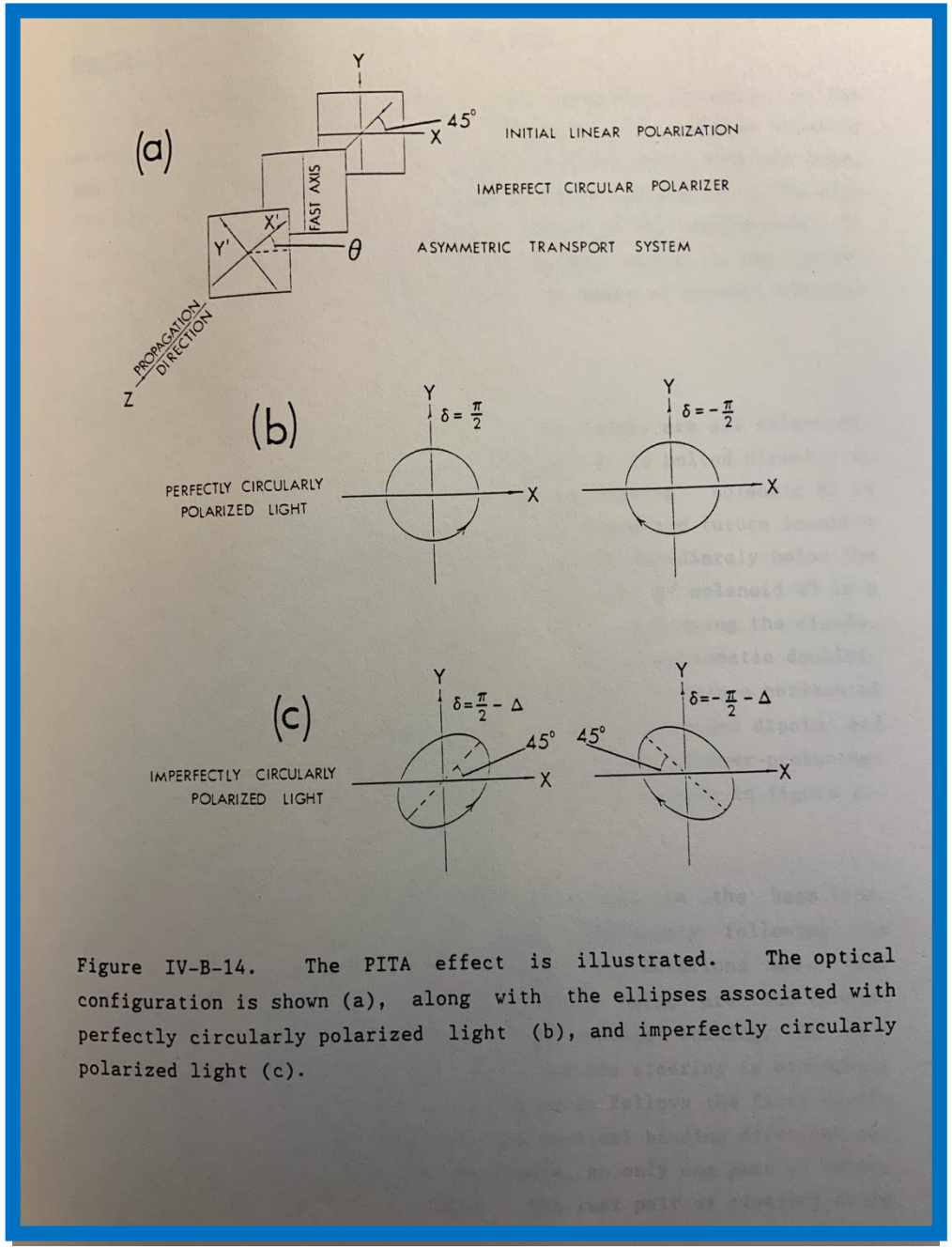
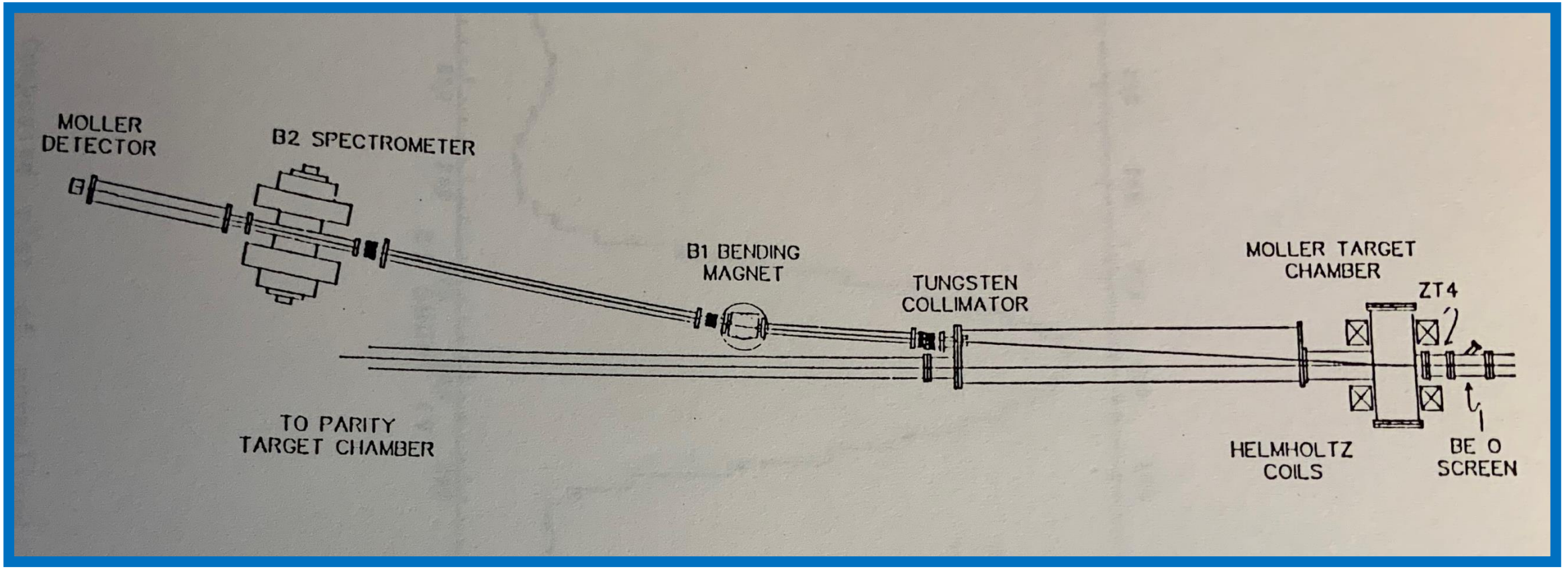
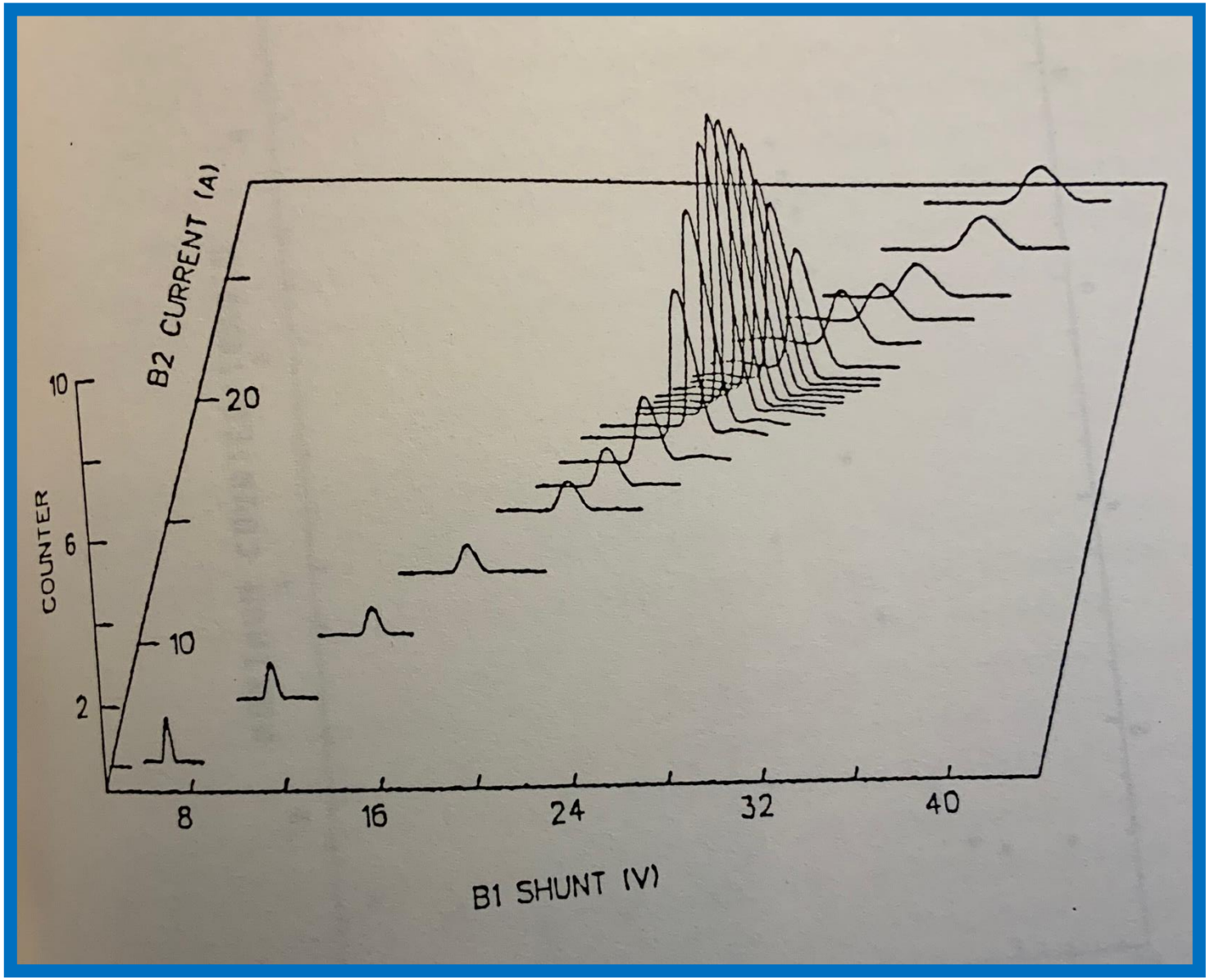


Figure IV-B-14. The PITA effect is illustrated. The optical configuration is shown (a), along with the ellipses associated with perfectly circularly polarized light (b), and imperfectly circularly polarized light (c).

Spectrometer for Moller Polarimetry



Moller Signal



Main Result of the Bates Experiment for Me

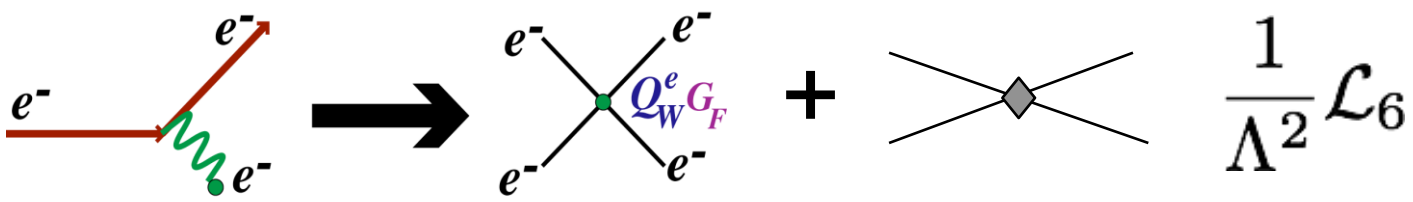
I started working with entirely new collaborators (Gordon, KK, Bob, etc.) who became the people that I have worked with for the rest of my career.

Next Step: Moller PVES ("Too Hard for Prescott")

electron target:

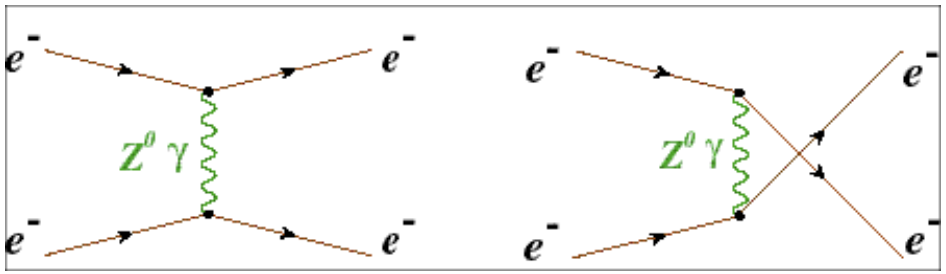
$$Q_W = 1 - 4\sin^2\theta_W$$

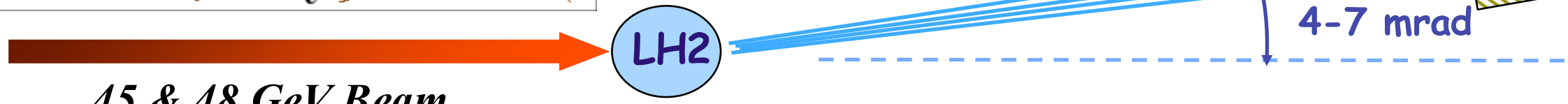
$APV \sim 8\times10^{-8} E_{beam}(1-4\sin^2\theta_W)$ ~100 ppb



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

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





45 & 48 GeV Beam
85% longitudinal polarization

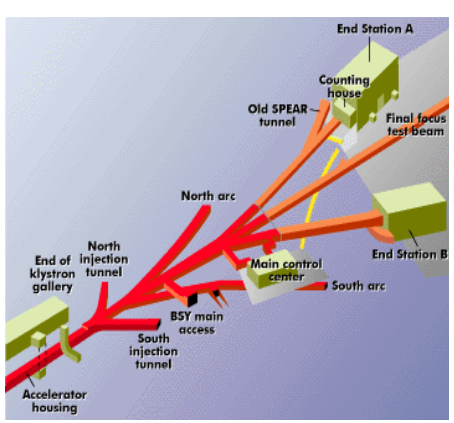
End Station A at SLAC

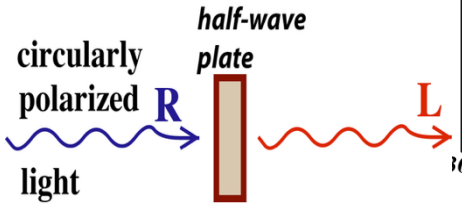
SLAC E158: 1997-2004

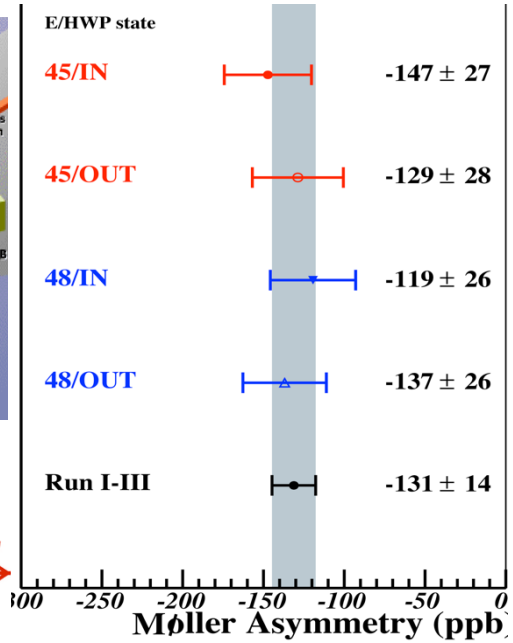
SLAC End Station A



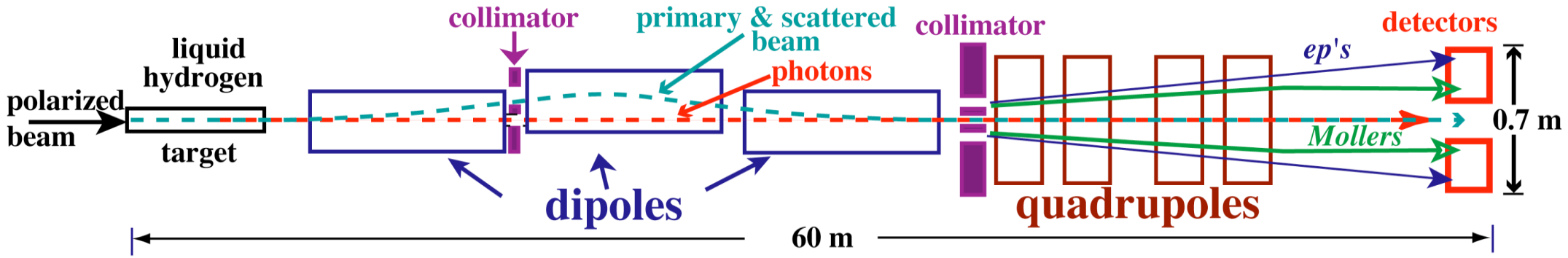
E158 Apparatus





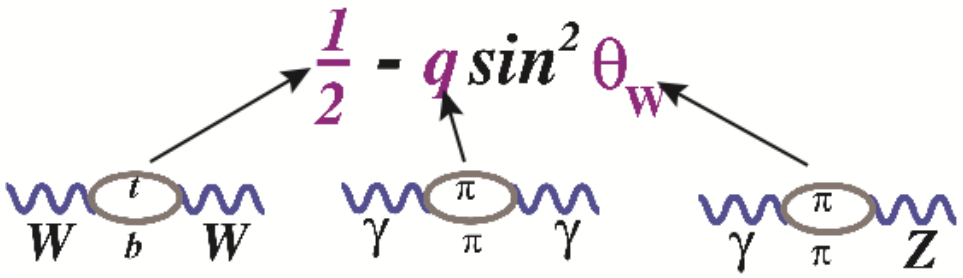






E158 Results

Tree-level prediction: ~ 250 ppb



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

Final E158 Result

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

Nature
Vol 435 26 May 2005
NEWS AND VIEWS

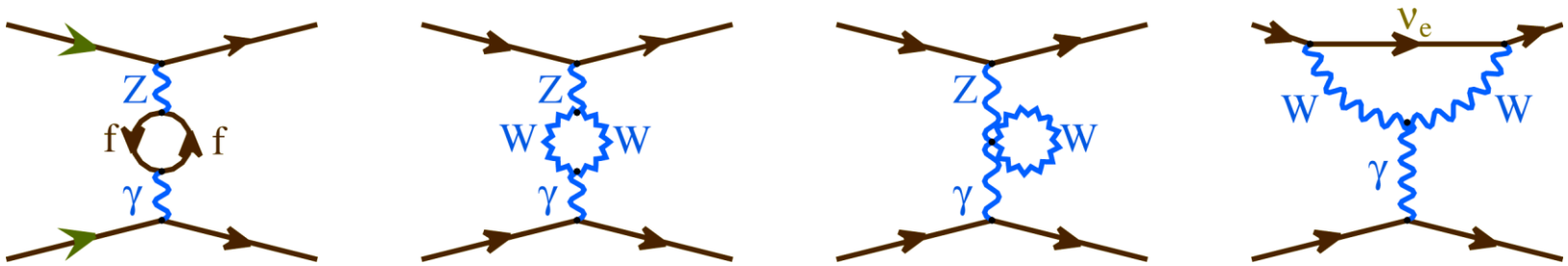
PARTICLE PHYSICS

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.

Czarnecki and Marciano (1995)



All New Collaborators

2005

Precision measurement of the weak mixing angle in Moller scattering

P.L. Anthony, R.G. Arnold, C. Arroyo, K. Bega, Jed Biesiada, Peter E. Bosted, G. Bower, J. Cahoon, R. Carr, G.D. Cates, Jian-Ping Chen, E. Chudakov, Mark S. Cooke, P. Decowski, A. Deur, W. Emam, R. Erickson, T. Fieguth, C. Field, J. Gao, M. Gary, K. Gustafsson, R.S. Hicks, R. Holmes, E.W. Hughes, T.B.Humensky, G.M. Jones, L.J. Kaufman, L. Keller, Yu.G. Kolomensky, Krishna S. Kumar, P. LaViolette, D. Lhuillier, R.M. Lombard-Nelsen, Z. Marshall, P. Mastromarino, R.D. McKeown, R. Michaels, J. Niedziela, M. Olson, K.D. Paschke, G.A. Peterson, R. Pitthan, D. Relyea, S.E. Rock, O. Saxton, J. Singh, P.A. Souder, Z.M. Szalata, J. Turner, B. Tweedie, A. Vacheret, D. Walz, T. Weber, J. Weisend, M. Woods, I. Younus

Epilog

Together with my new colleagues, as well as other collaborations, a rich program of PVES was successfully undertaken.