

Low Energy Tests of the Standard Model

- * PAST
- * PRESENT
- * FUTURE

Emlyn Hughes
Spin 2004
Trieste
October 14, 2004

Electroweak Mixing Angle

$$e = g \sin\theta_w$$

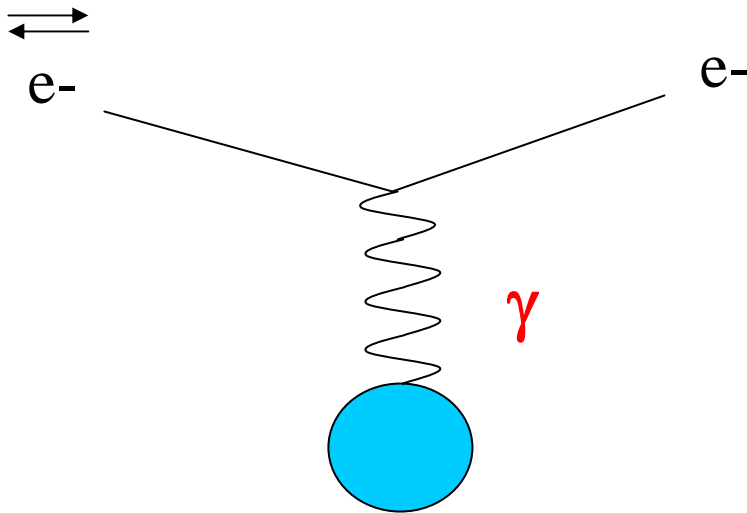
Characterizes the mixing between the weak and EM interaction in the electroweak theory

$$\sin^2\theta_w = 1 - M_w^2 / M_Z^2$$

3 Types of Measurements

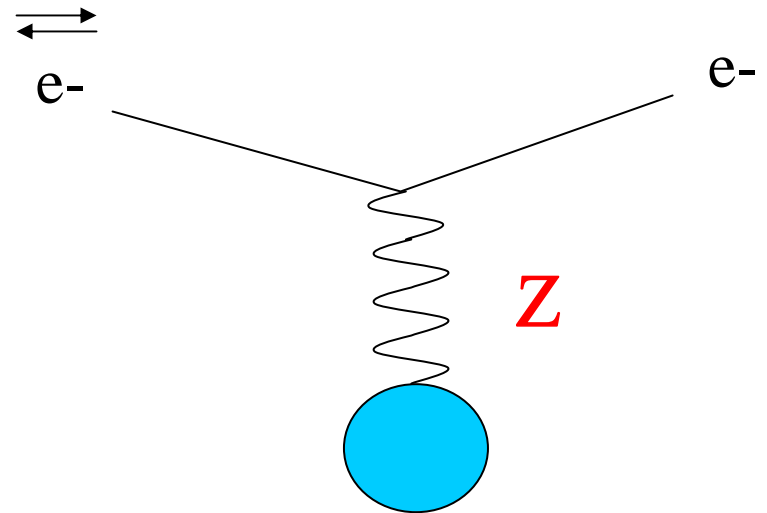
- * Electron scattering (parity violation)
- * Atomic parity violation
- * Neutrino physics (NC/CC cross section)

Parity Violation in Polarized Electron Scattering



unpolarized quarks or electrons or protons

Parity conserving



Parity violating

Parity Violation in the Electroweak Theory

$$A^{PV} = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L}$$

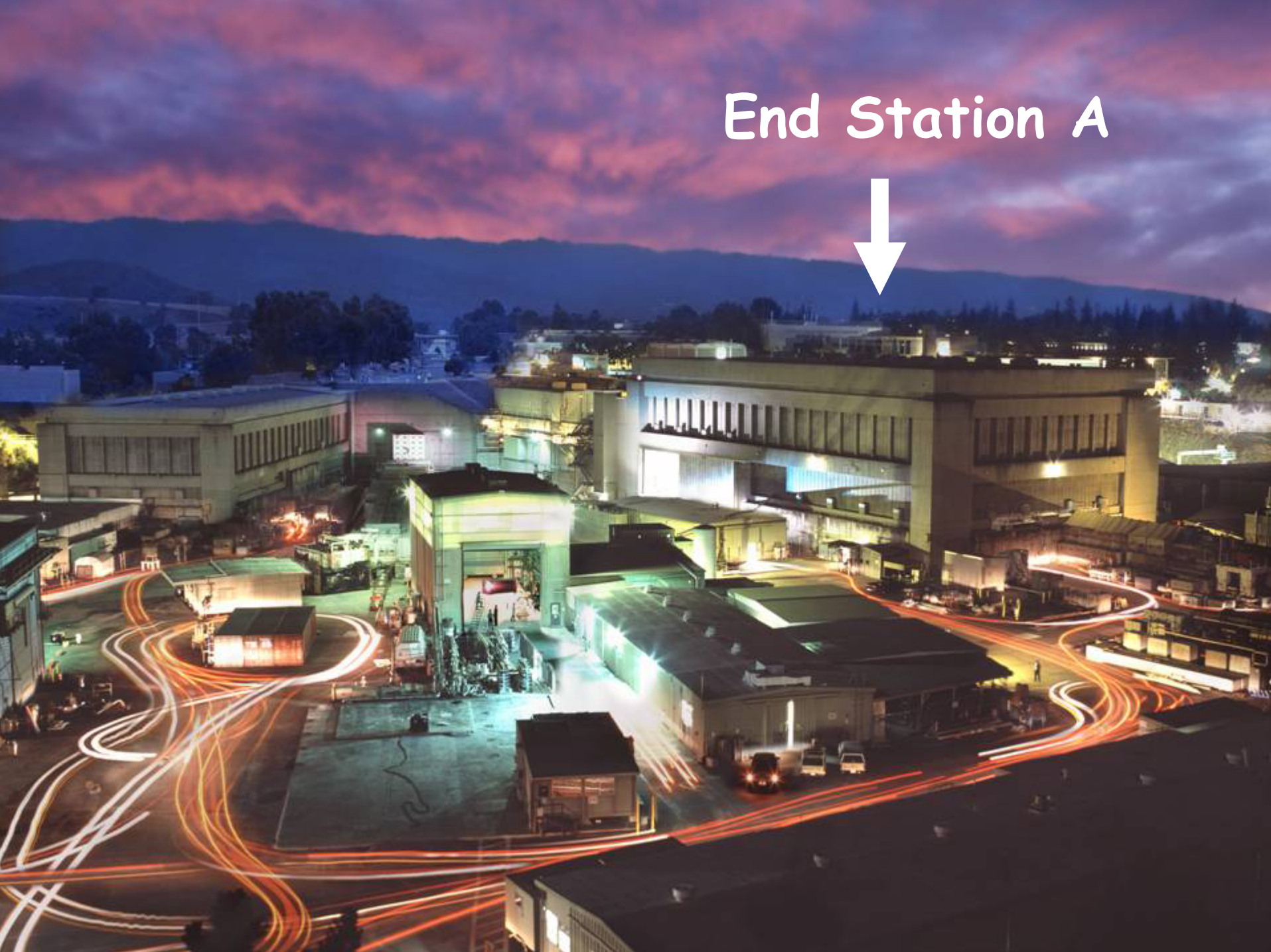
$$A^{PV} \sim \frac{2A_W A_{EM}}{A_W^2 + A_{EM}^2} \sim 2 \frac{A_W}{A_{EM}} \sim 2 \frac{\frac{g^2}{m_Z^2 + q^2}}{\frac{e^2}{q^2}}$$

$$A^{PV} \sim 2 \frac{q^2}{m_Z^2}$$

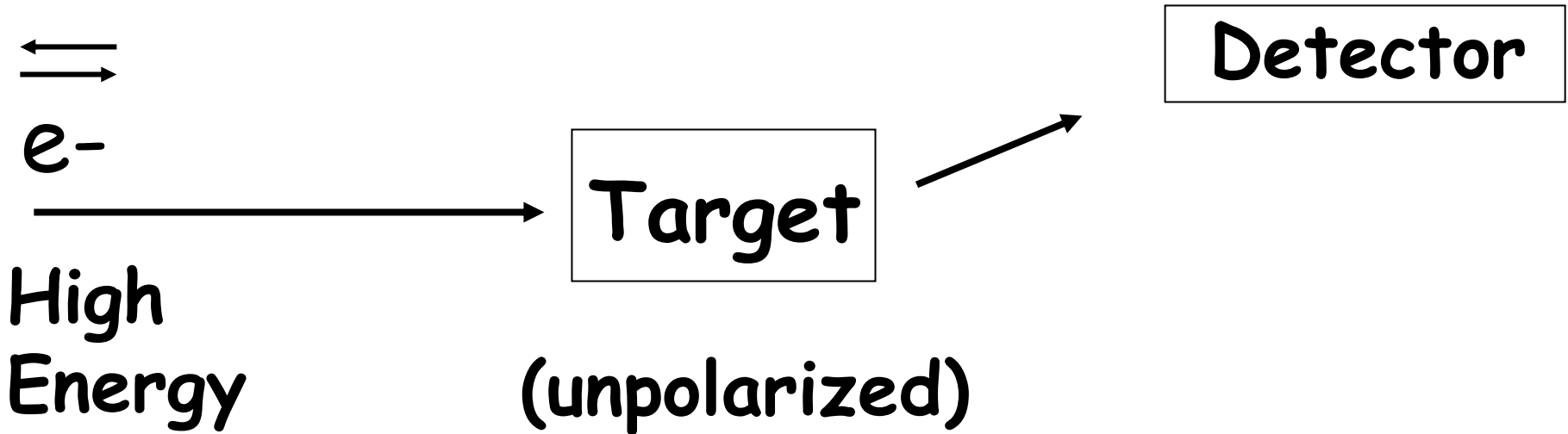
SLAC



End Station A



SLAC Parity Experiments



Parity-violating asymmetry

$$A^{PV} = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L}$$

SLAC E80

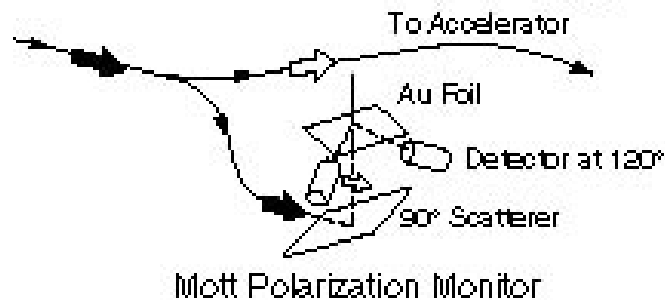
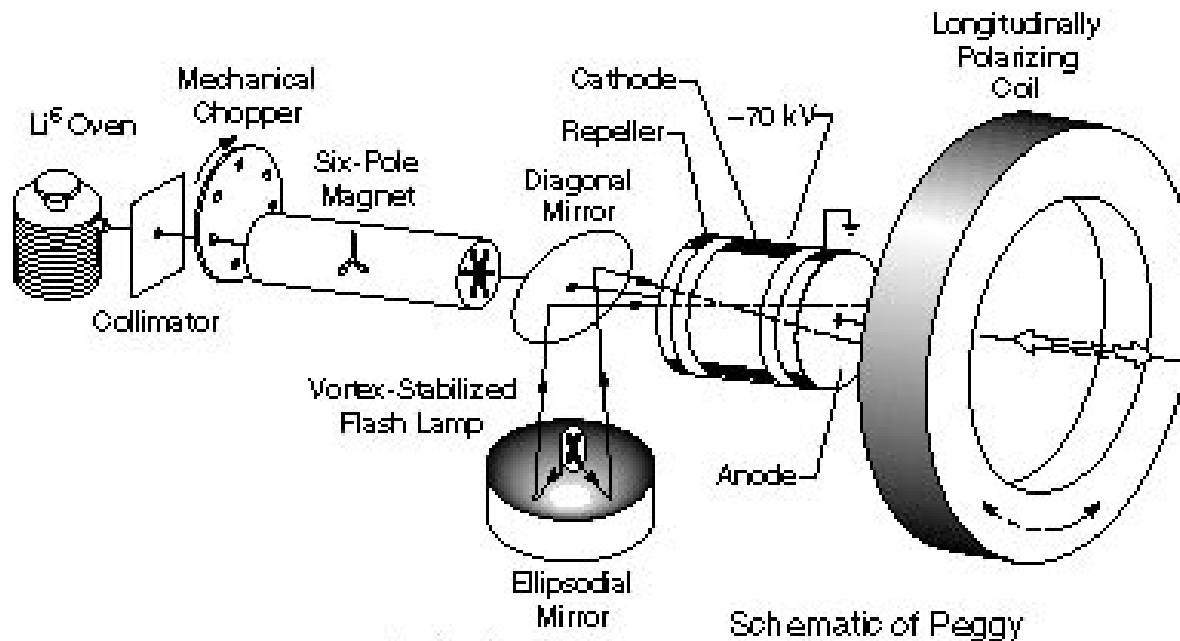
Deep Inelastic Scattering of Polarized Electrons by Polarized Protons*

M. J. Alguard, W. W. Ash, G. Baum, J. E. Clendenin, P. S. Cooper, D. H. Coward, R. D. Ehrlich, A. Etkin, V. W. Hughes, H. Kobayakawa, K. Kondo, M. S. Lubell, R. H. Miller, D. A. Palmer, W. Raith, N. Sasao, K. P. Schüler, D. J. Sherden, C. K. Sinclair, and P. A. Souder
University of Bielefeld, Bielefeld, West Germany, and City University of New York, New York, New York 10031, and Nagoya University, Nagoya, Japan, and Stanford Linear Accelerator Center, Stanford, California 94305, and University of Tsukuba, Ibaraki, Japan, and Yale University, New Haven, Connecticut 06520

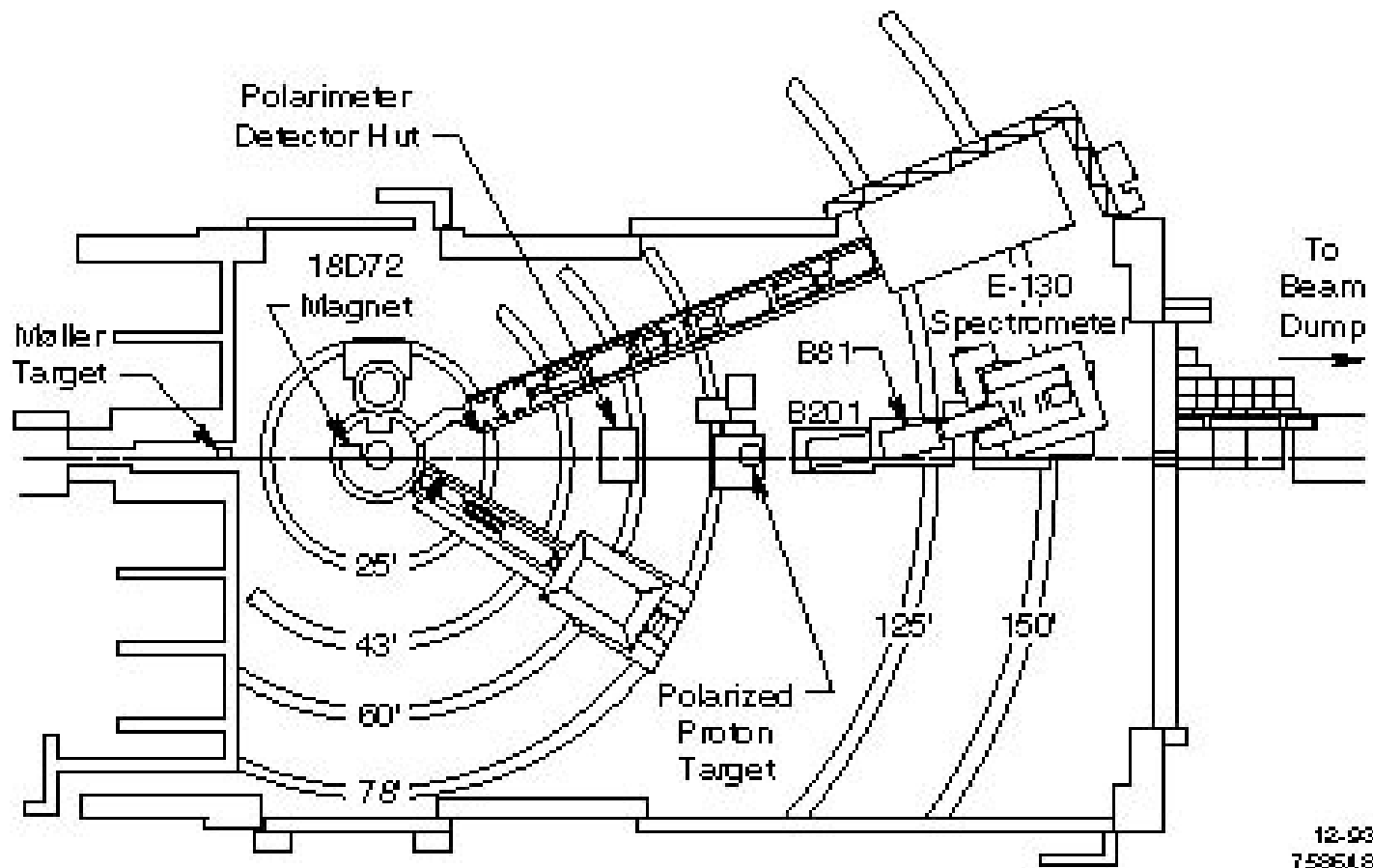
(Received 5 August 1976)

We report measurements of the asymmetry in deep inelastic scattering of longitudinally polarized electrons by longitudinally polarized protons. The antiparallel-parallel asymmetries are positive and large in agreement with predictions of quark-parton models of the proton. A limit is obtained on parity nonconservation in the scattering of longitudinally polarized electrons by unpolarized nucleons.

Yale E80 Polarized Source



SLAC End Station A



SLAC E95

PHYSICAL REVIEW D

VOLUME 18, NUMBER 7

1 OCTOBER 1978

Search for parity violation in deep-inelastic scattering of polarized electrons by unpolarized deuterons

W. B. Atwood, R. L. A. Cottrell, H. DeStaebler, R. Miller, H. Pessard,* C. Y. Prescott, L. S. Rochester, and
R. E. Taylor

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

M. J. Alguard, J. Clendenin, P. S. Cooper, R. D. Ehrlich,[†] V. W. Hughes, and M. S. Lubell
Yale University, New Haven, Connecticut 06520

G. Baum and K. P. Schüler

University of Bielefeld, Bielefeld, West Germany

K. Lübelmeyer

Technische Hochschule Aachen, Aachen, West Germany

(Received 17 April 1978)

We report on recent asymmetry measurements for inelastic scattering of longitudinally polarized electrons from an unpolarized deuterium target at 19.4 GeV. Using the SLAC 20-GeV/c and 8-GeV/c spectrometers, the helicity-dependent cross-section asymmetries were measured at Q^2 values of 1.2 and 4.2 (GeV/c)², and were found to be less than 2×10^{-3} and 7×10^{-3} , respectively.

Results on Parity Violation

E80

$$A^{LR} < 5 \times 10^{-3} \quad \text{at } Q^2 \sim 1.4, 2.7 \text{ GeV}^2$$

E95

$$A^{LR} < 3.2 \times 10^{-3} \quad \text{at } Q^2 \sim 4 \text{ GeV}^2$$

*Not sensitive to electroweak mixing
in the Standard Model*

First Measurements of Electroweak Mixing

SLAC E122

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING [☆]

C.Y. PRESCOTT, W.B. ATWOOD, R.L.A. COTTRELL, H. DeSTAEBLER, Edward L. GARWIN,
A. GONIDEC ¹, R.H. MILLER, L.S. ROCHESTER, T. SATO ², D.J. SHERDEN, C.K. SINCLAIR,
S. STEIN and R.E. TAYLOR

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

J.E. CLENDENIN, V.W. HUGHES, N. SASAO ³ and K.P. SCHÜLER

Yale University, New Haven, CT 06520, USA

M.G. BORGHINI

CERN, Geneva, Switzerland

K. LÜBELSMEYER

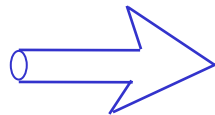
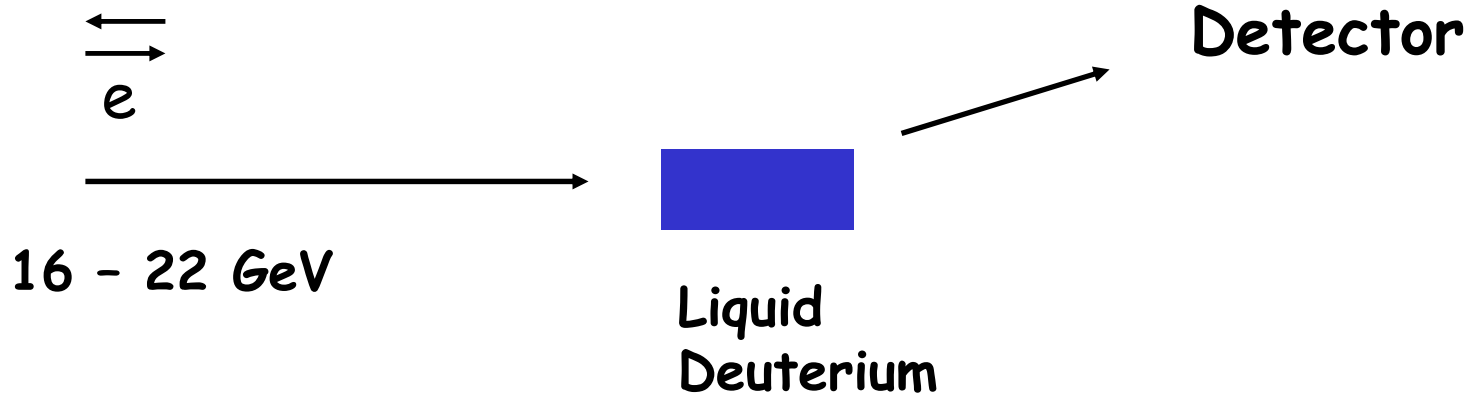
Technische Hochschule Aachen, Aachen, West Germany

and

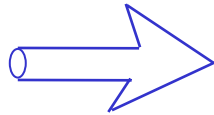
W. JENTSCHKE

II. Institut für Experimentalphysik, Universität Hamburg, Hamburg, West Germany

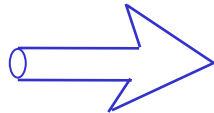
SLAC E122



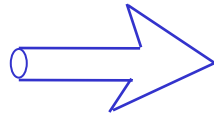
GaAs source



High current



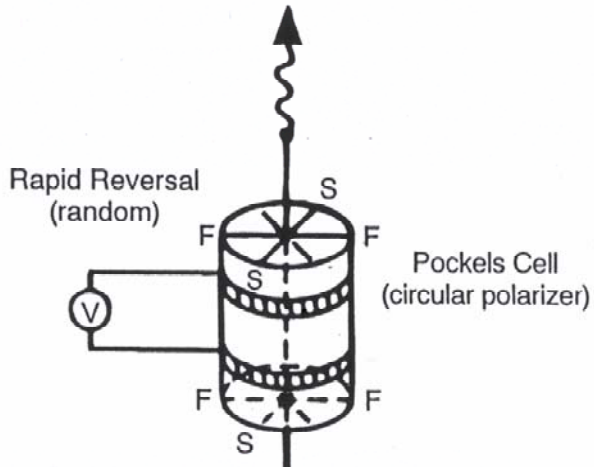
30 cm target



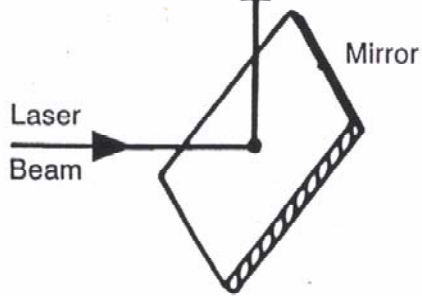
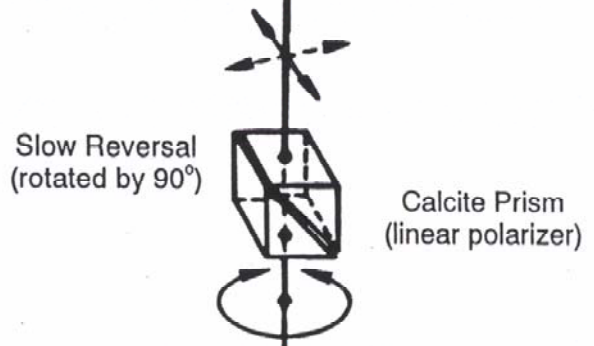
Dedicated run

Polarized Laser Beam to the Ga As Cathode

120 Hz →

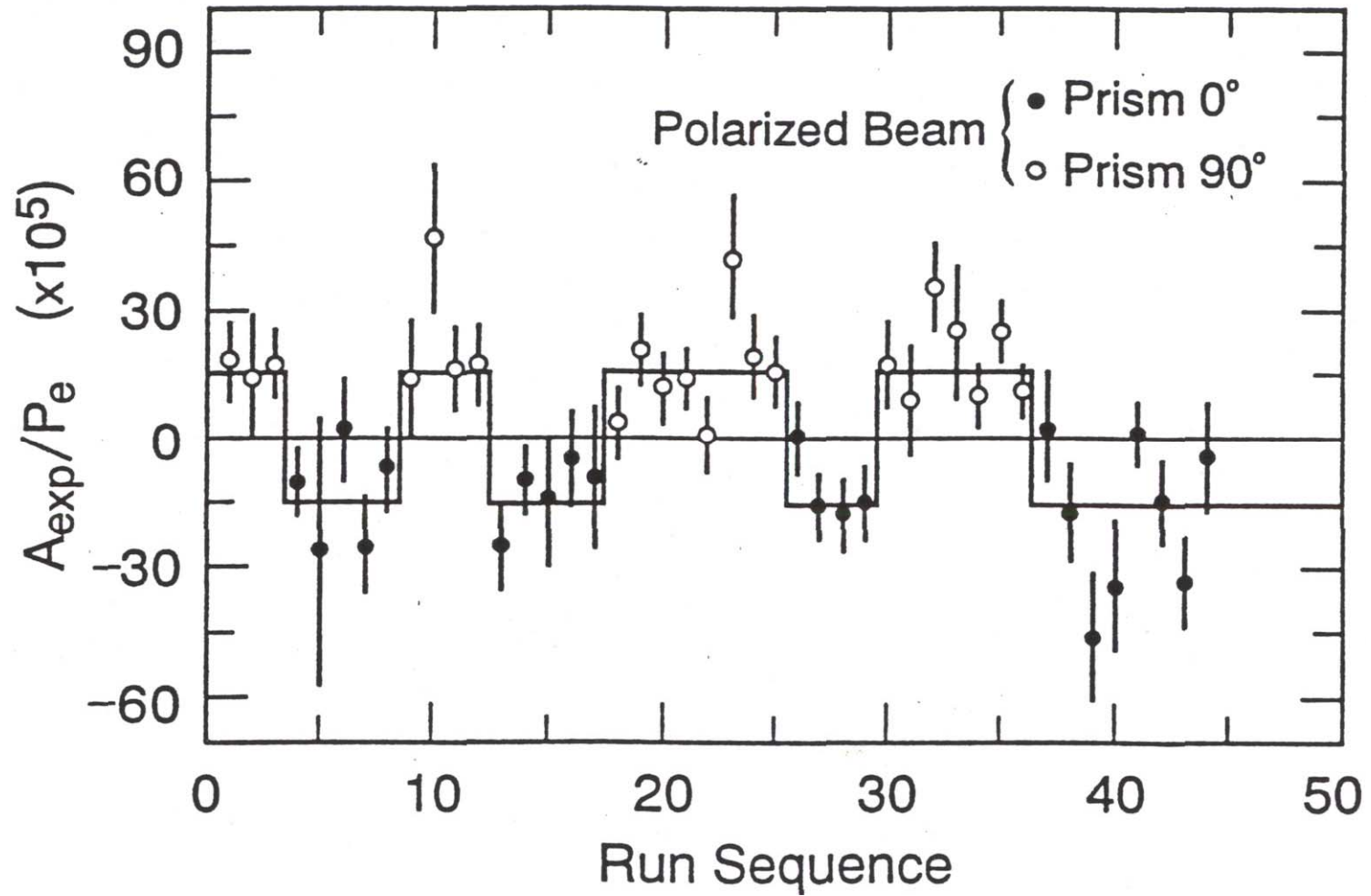


Reversed every few runs →



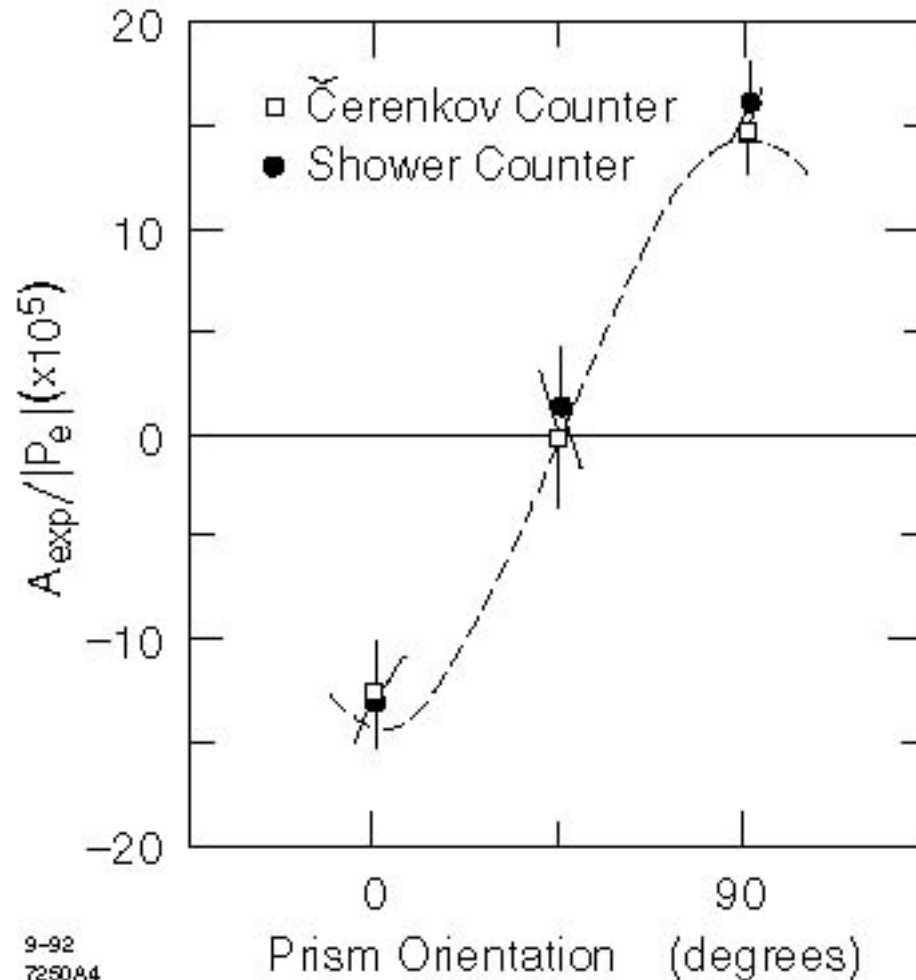
Optical Reversal Scheme

SLAC E122 waveplate reversal



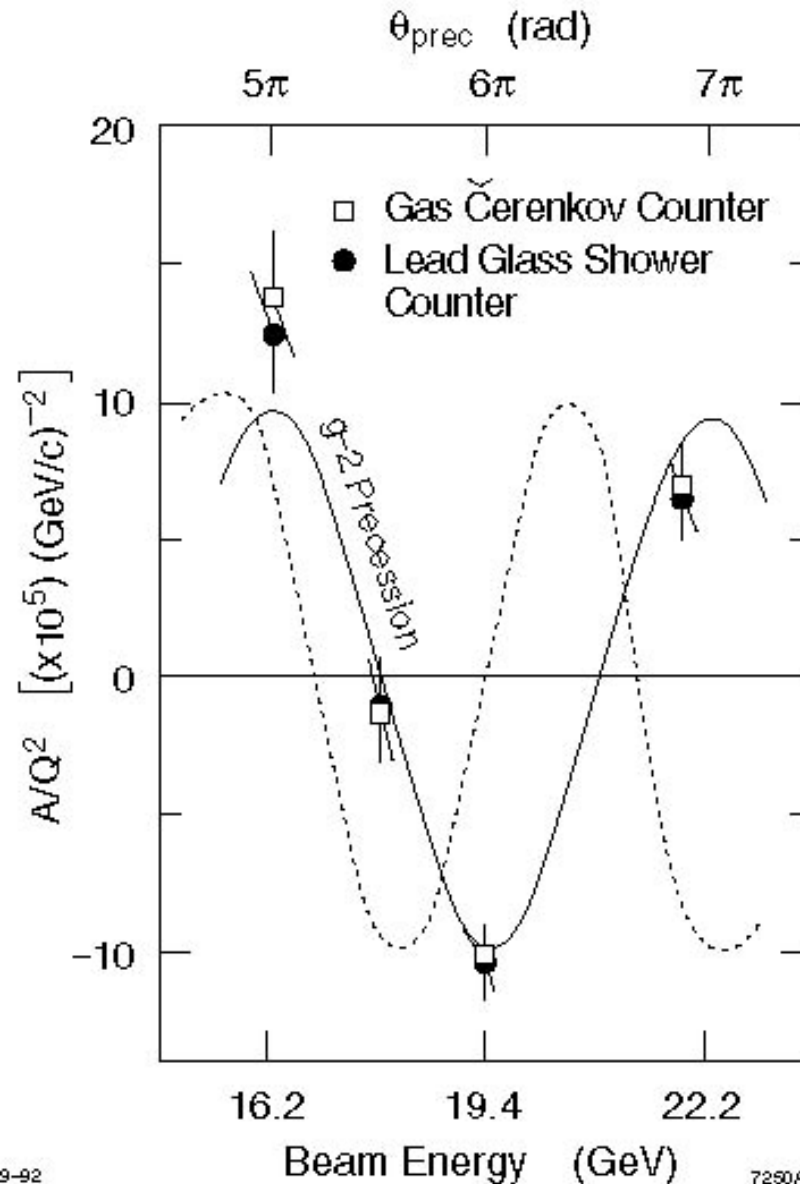
SLAC E122 waveplate reversal

Parity-violating
asymmetry



SLAC E122 Energy Scan

Parity-violating
asymmetry

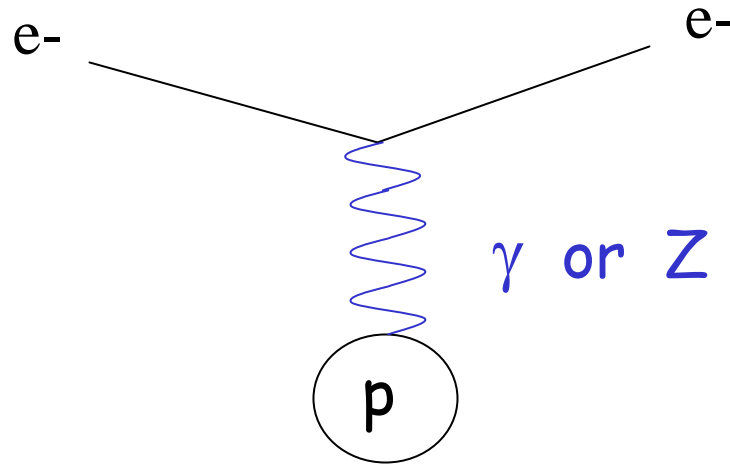


SLAC E122 Result (1978)

$$\sin^2\theta_w = 0.224 \pm 0.020$$

First definitive measurement of mixing between
the weak and electromagnetic interaction

Atomic Parity Violation

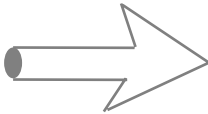


$$A^{LR} \sim 2 \frac{q^2}{m_Z^2} \sim 2 \frac{m_e^2 \alpha^2}{m_Z^2} \sim 10^{-14}$$

Experiment

Z^3 Law  Heavy Atoms

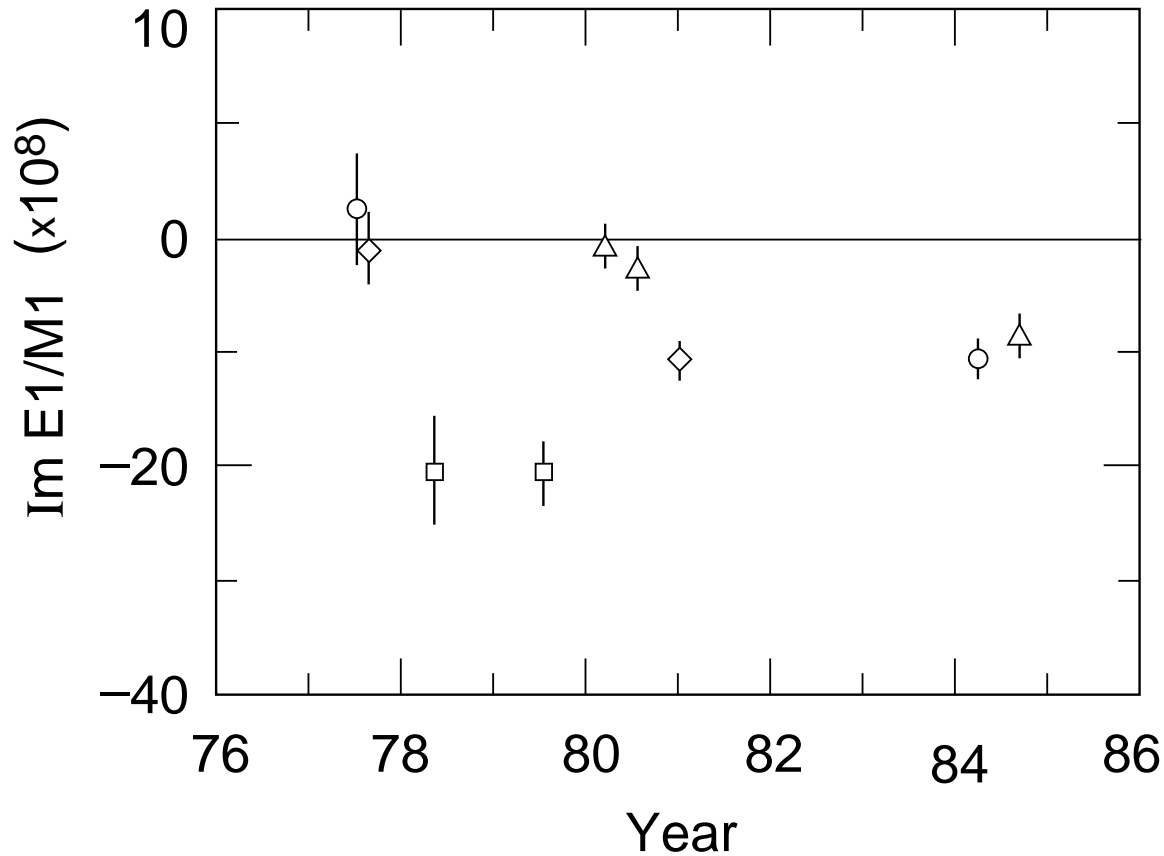
Theory

PV Signal  $\sin^2\theta_w$

Bismuth **$Z = 83$**

Atomic Parity Violation

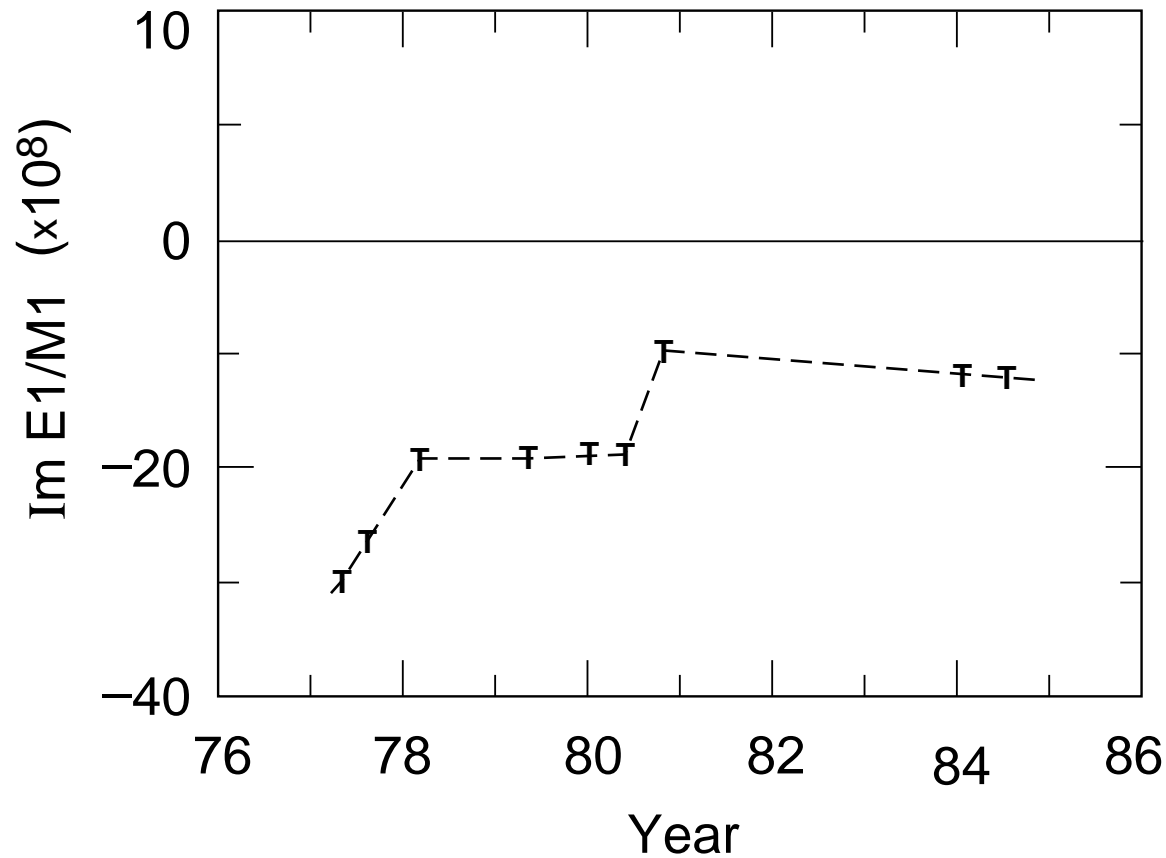
- Oxford
- ◇ Seattle
- △ Moscow
- Novosibirsk



Bismuth

Atomic Parity Violation

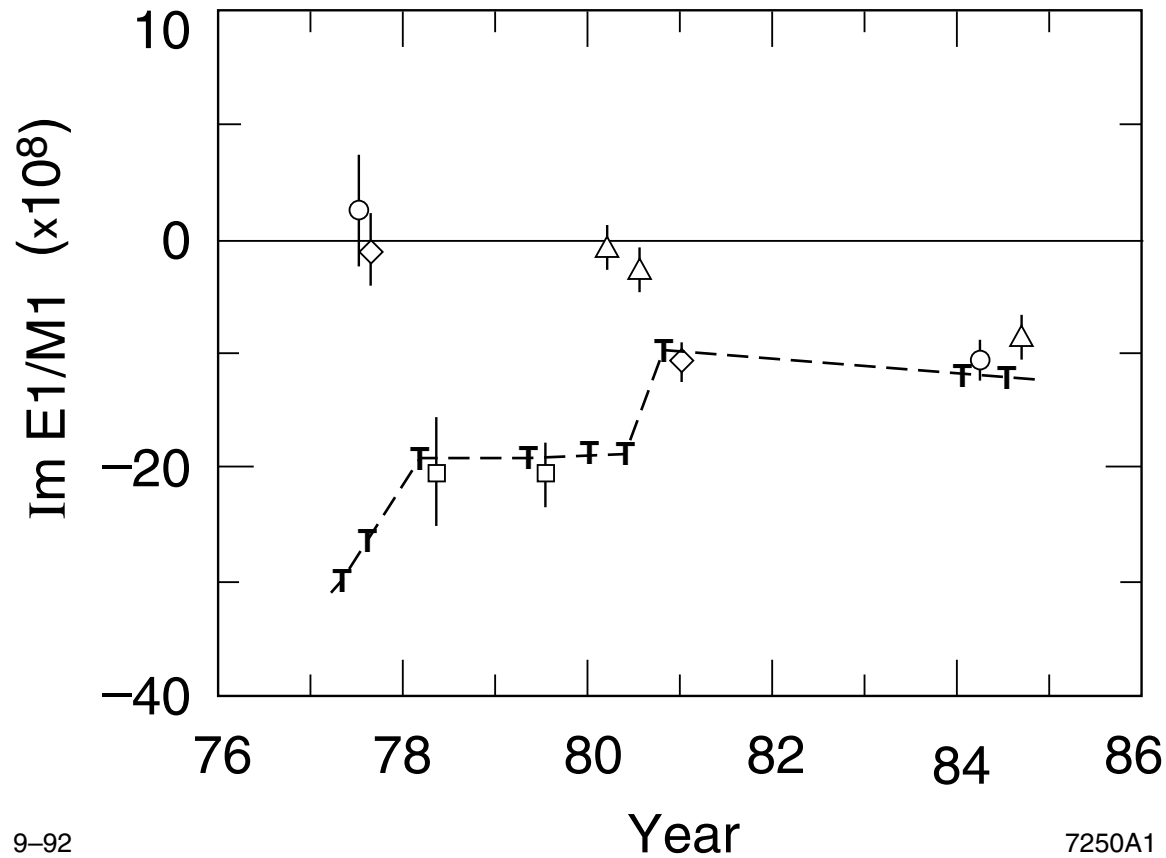
τ Theory



Bismuth

Atomic Parity Violation

○ Oxford ◇ Seattle τ Theory
△ Moscow □ Novosibirsk



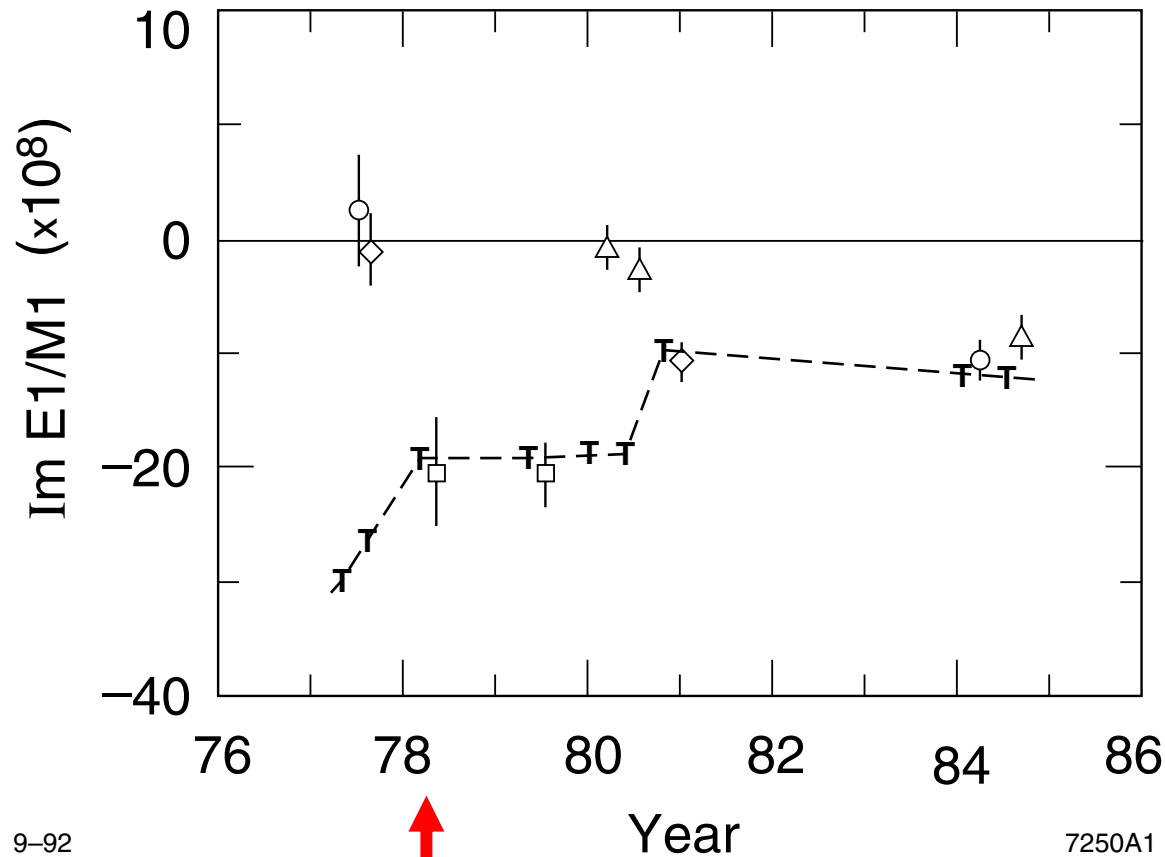
9-92

7250A1

Bismuth

Atomic Parity Violation

○ Oxford ◇ Seattle τ Theory
△ Moscow □ Novosibirsk



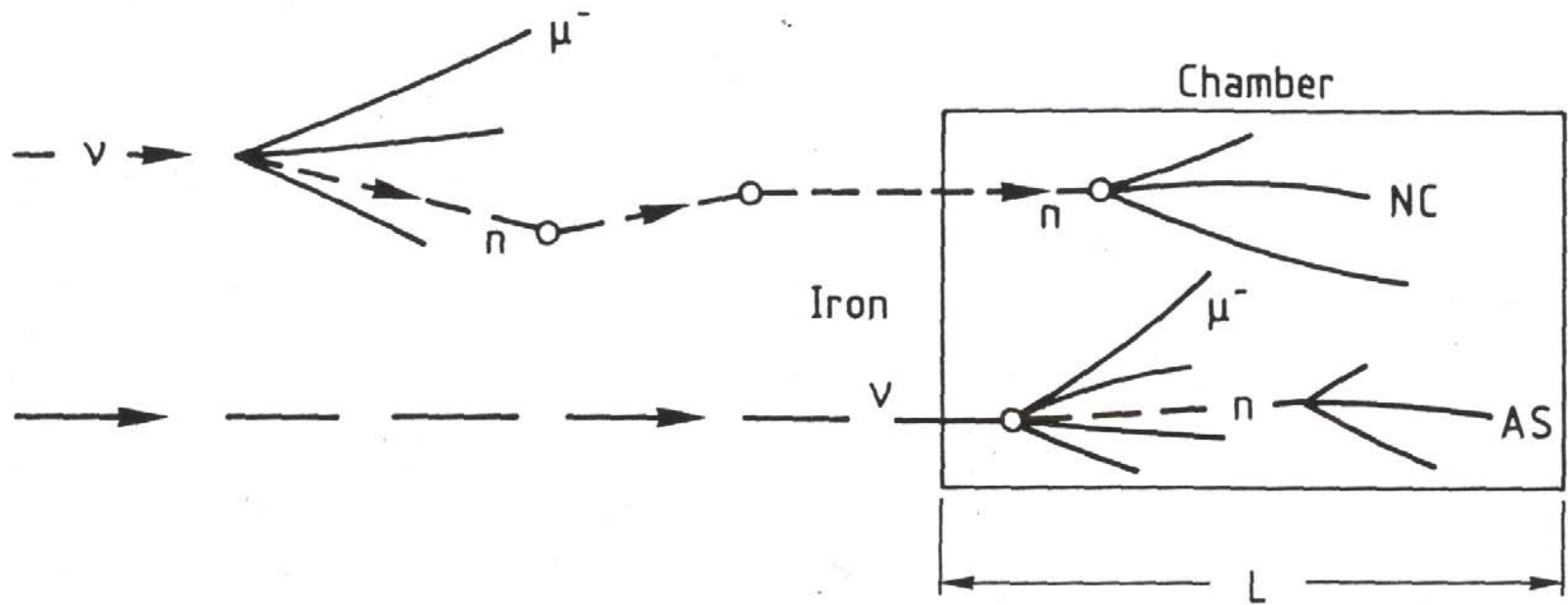
9-92

E122

7250A1

Bismuth

Neutrino Physics

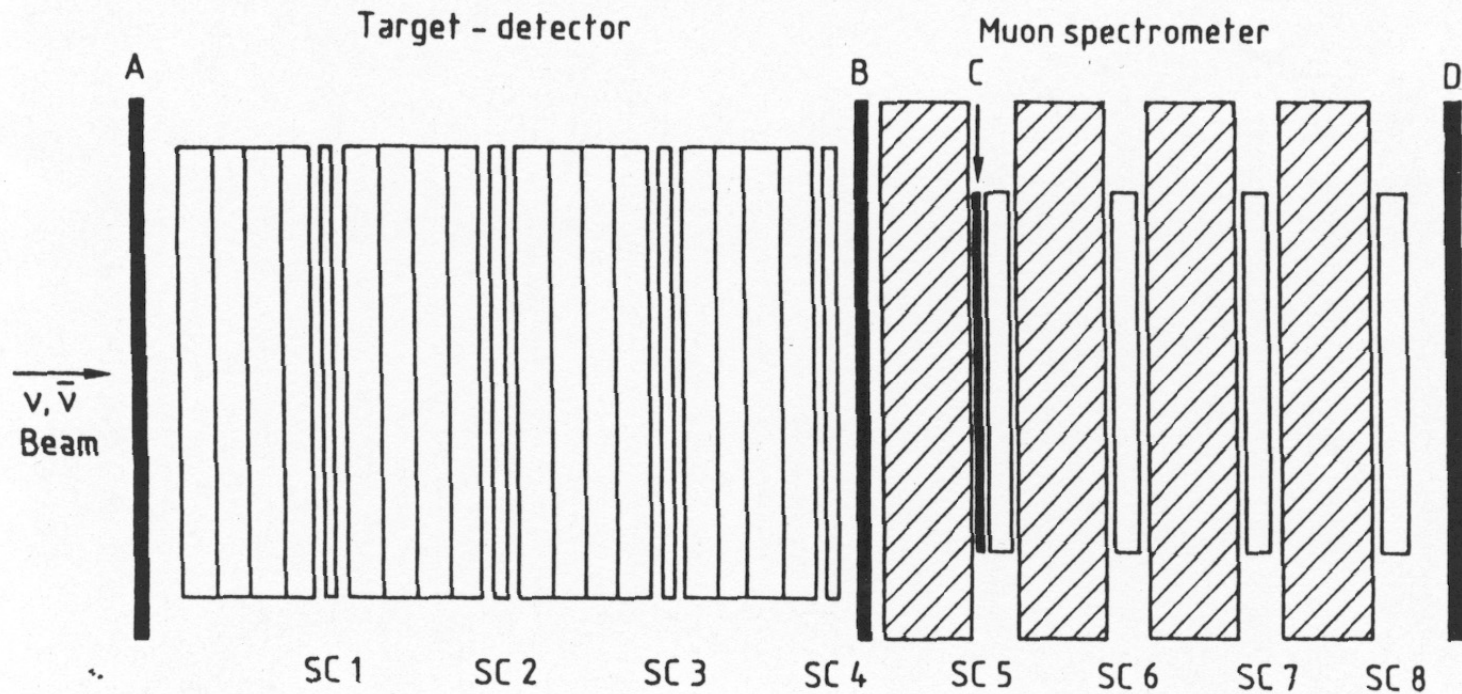


Gargamelle

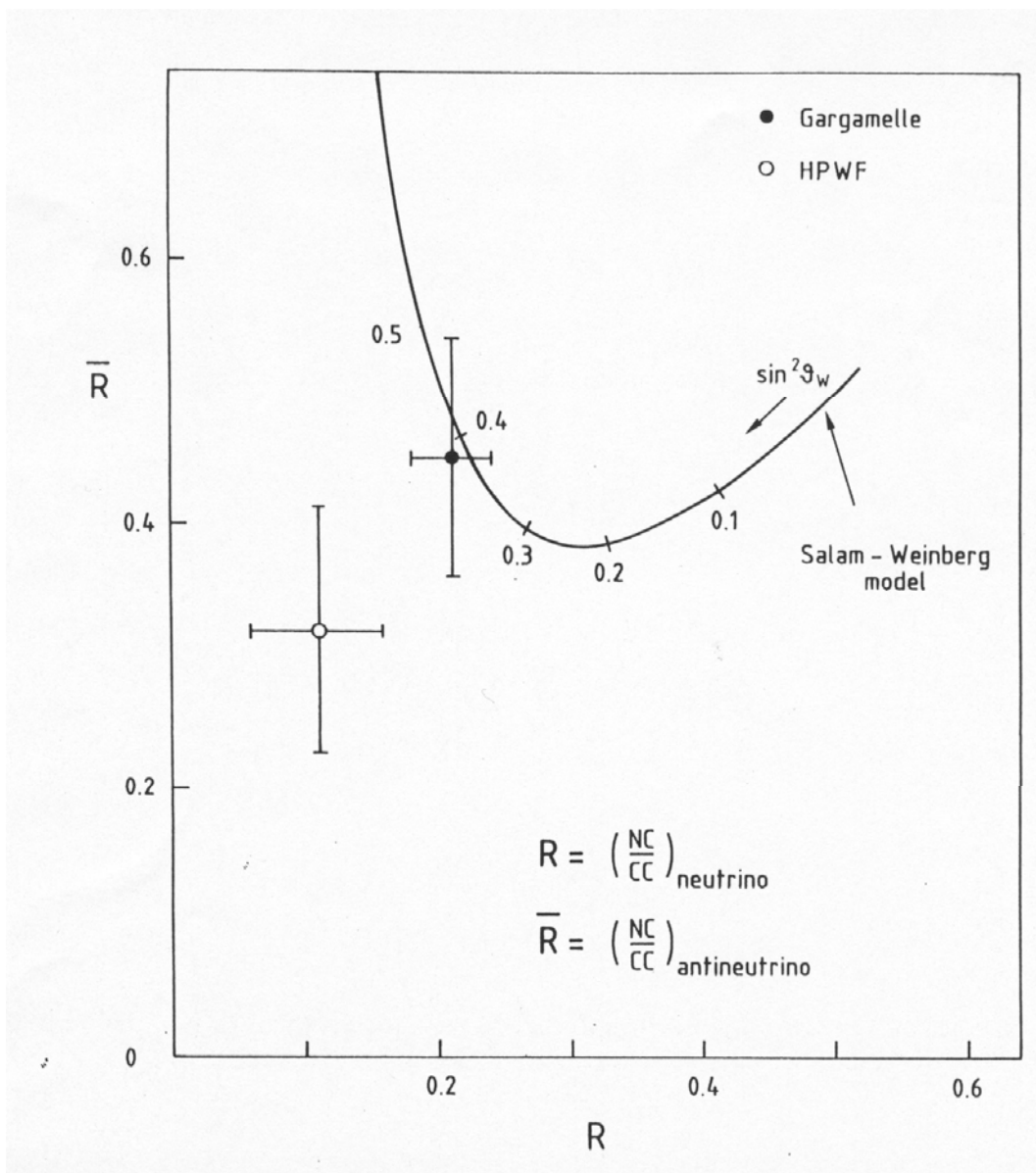
Bubble Chamber

HPWF Neutrino Detector

(Harvard, Pennsylvania, Wisconsin, Fermilab)



1974



Neutral Currents in High-Energy Neutrino Collisions: An Experimental Search*

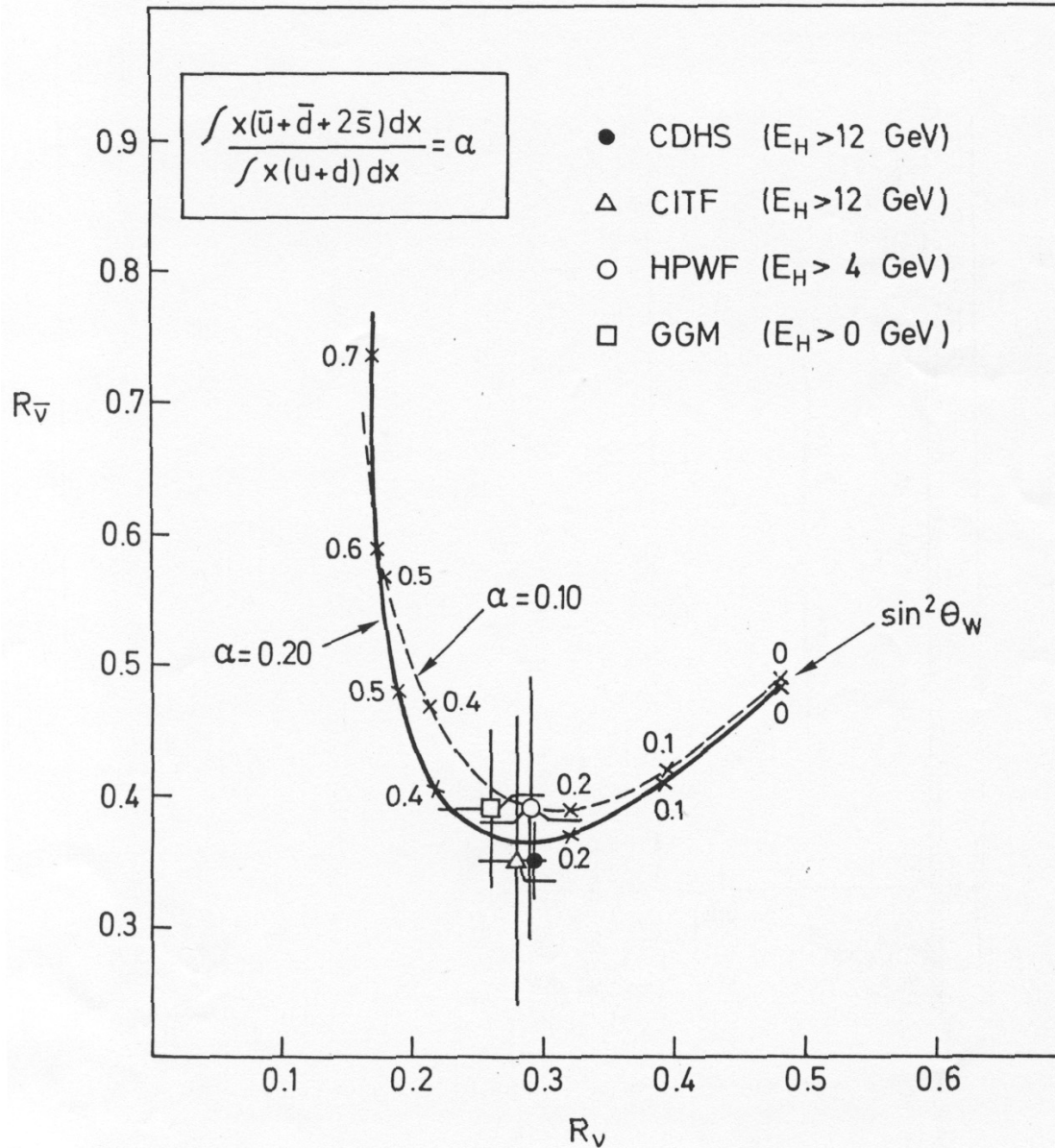
B. C. Barish, J. F. Bartlett, K. W. Brown, D. Buchholz, F. Jacquet,†
F. S. Merritt, F. J. Sciulli, and H. Suter‡
California Institute of Technology, Pasadena, California 91125

and

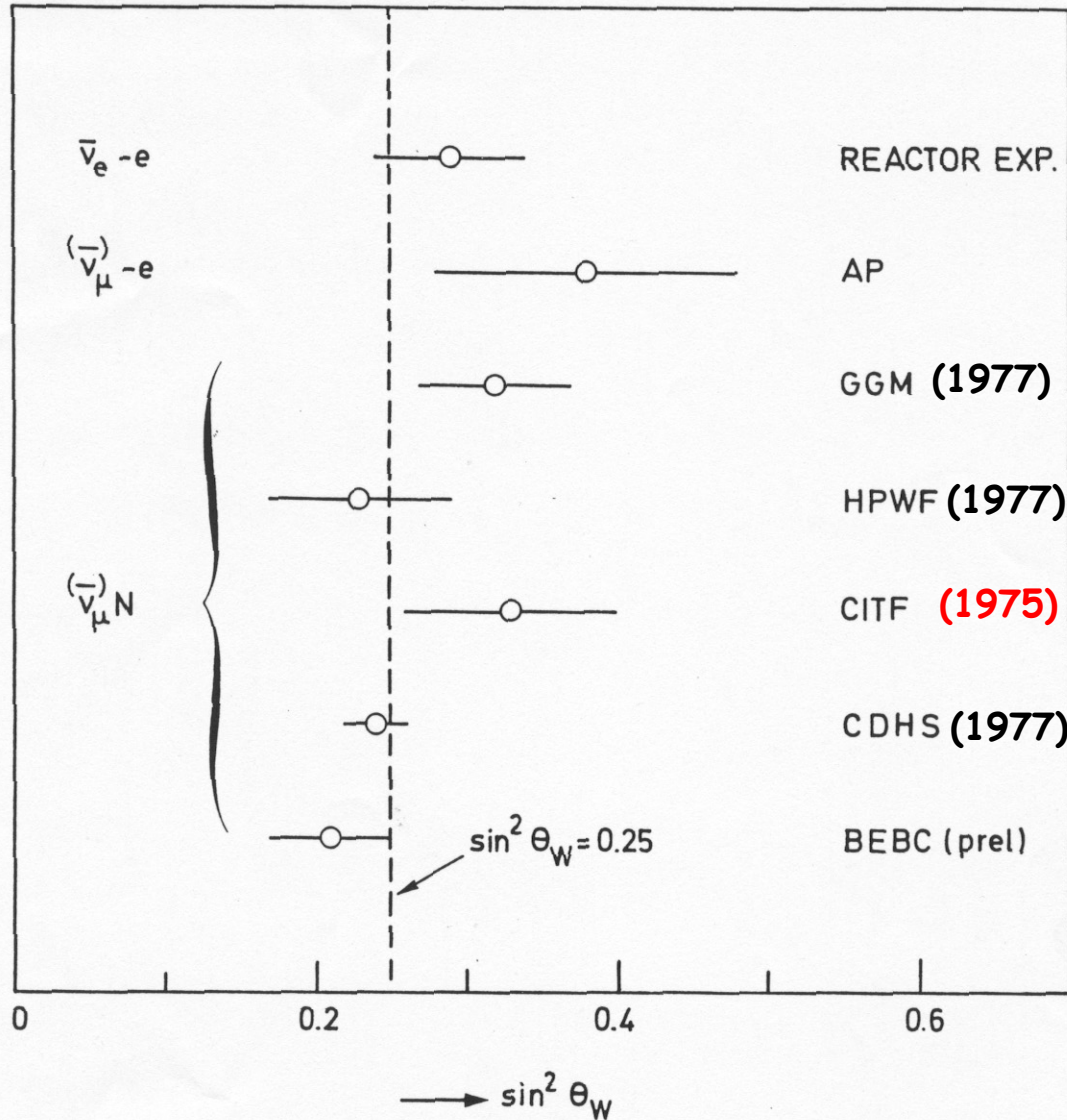
H. E. Fisk and G. Krafczyk
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 23 December 1974)

A search for events with no final-state muon, as expected in the neutral-current interactions $\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \nu_\mu(\bar{\nu}_\mu) + \text{hadrons}$, has been carried out by using the California Institute of Technology-Fermilab neutrino detector and narrow-band neutrino beam. A clear signal of events with no apparent final-state muon has been observed. Furthermore, missing energy in the final state for these events provides strong evidence for the existence of a final-state ν .

1978

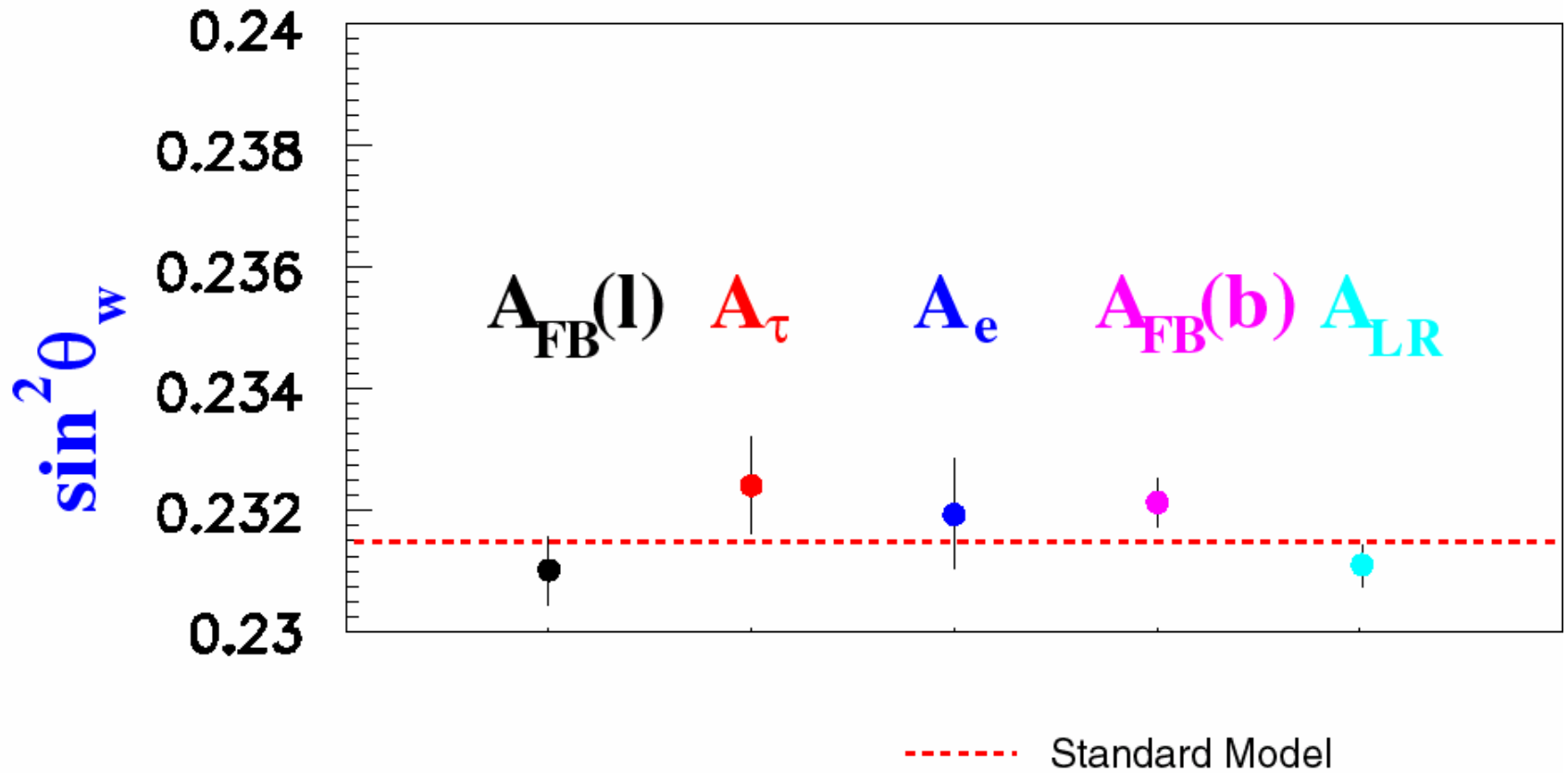


1978



TODAY...

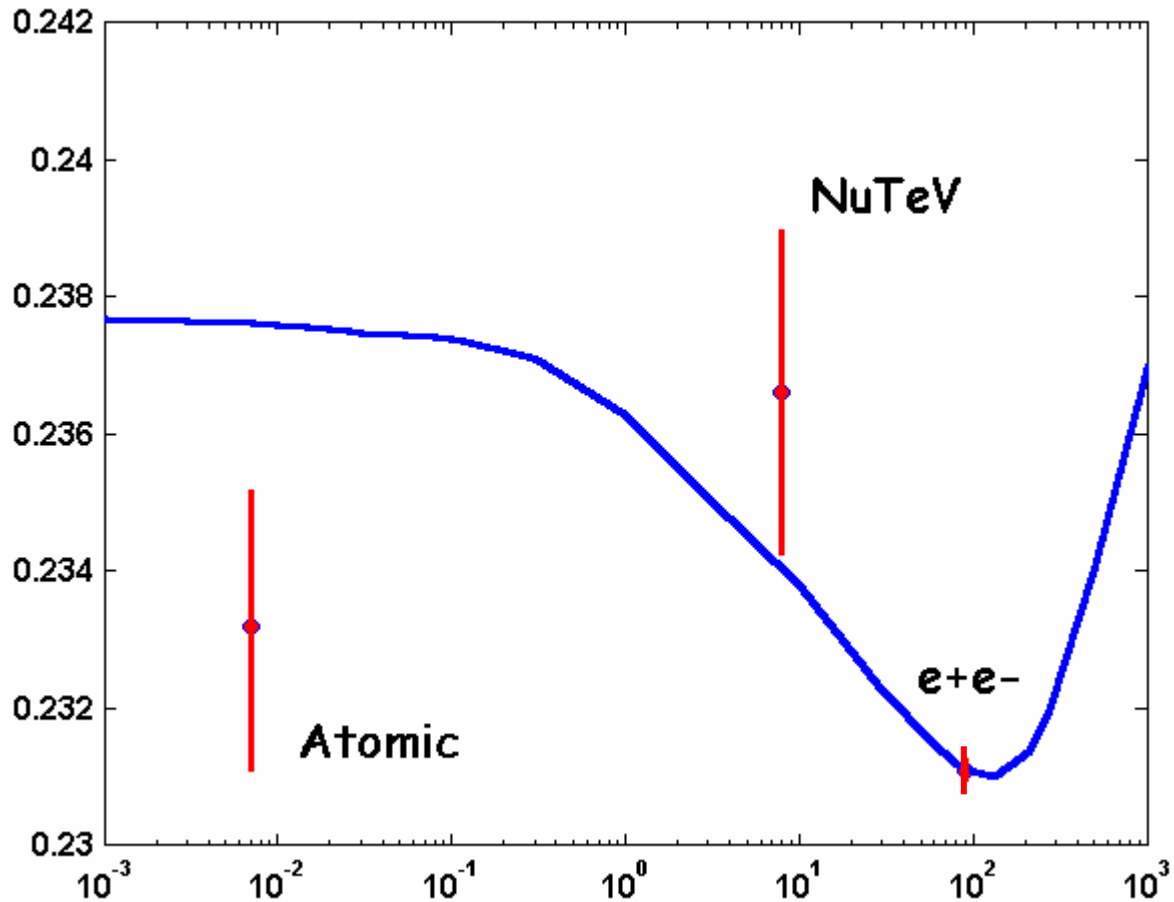
LEP and SLC e^+e^- collider



$\Delta \sin^2 \theta_w = 0.00016$ (PDG2004) from Z pole measurements

Status in 1999

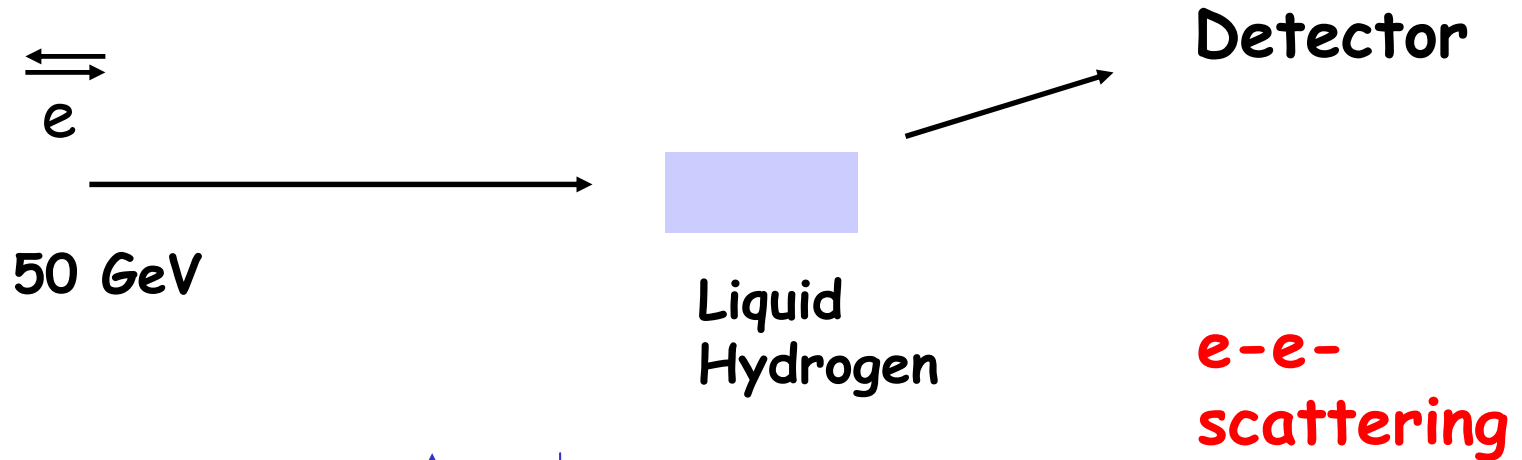
$\sin^2\theta_w$



$\sim 5\%$

Q (GeV)

SLAC Experiment E158



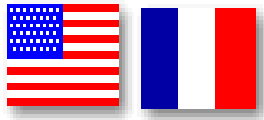
$$A^{PV} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Without electroweak radiative corrections,

$$A^{PV} = \frac{m E G_F}{\sqrt{2\pi} \alpha} \frac{16 \sin^2 \theta}{(3 + \cos^2 \theta)^2} \left(\frac{1}{4} - \sin^2 \theta_w \right)$$

In practice: $A^{PV} \sim 1.5 \times 10^{-7}$

E158 Collaboration

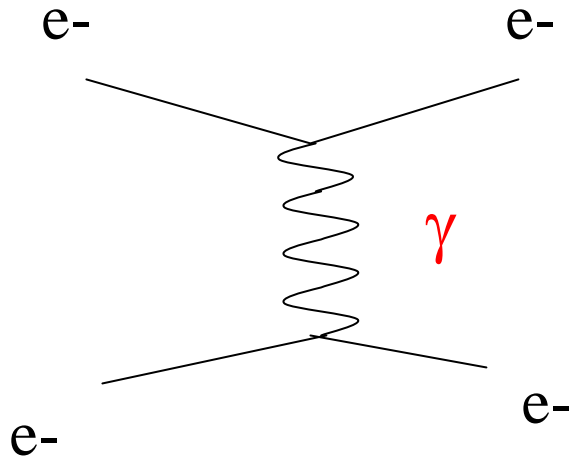


- UC Berkeley
- Caltech
- Jefferson Lab
- Princeton
- Saclay
- SLAC
- Smith College
- Syracuse
- UMass
- Virginia

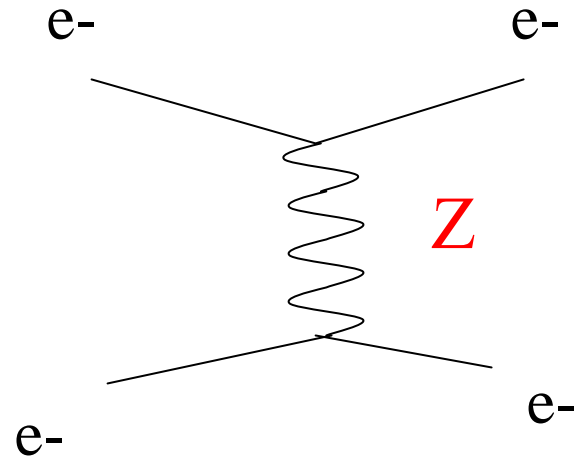
7 Ph.D. Students
60 physicists

Sept 97: EPAC approval
1998-99: Design and Beam Tests
2000: Funding and construction
2001: Engineering run
2002: Physics Runs 1 (Spring), 2 (Fall)
2003: Physics Run 3 (Summer)

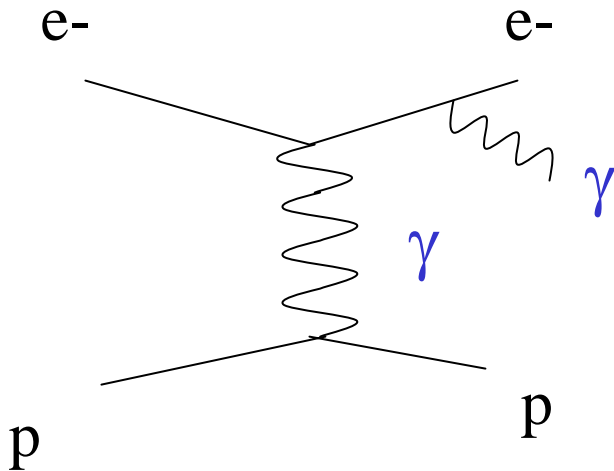
Scattering Processes



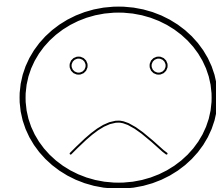
Parity-conserving



Parity-violating



Background



Challenges

I. Statistics

II. Beam monitoring & resolution

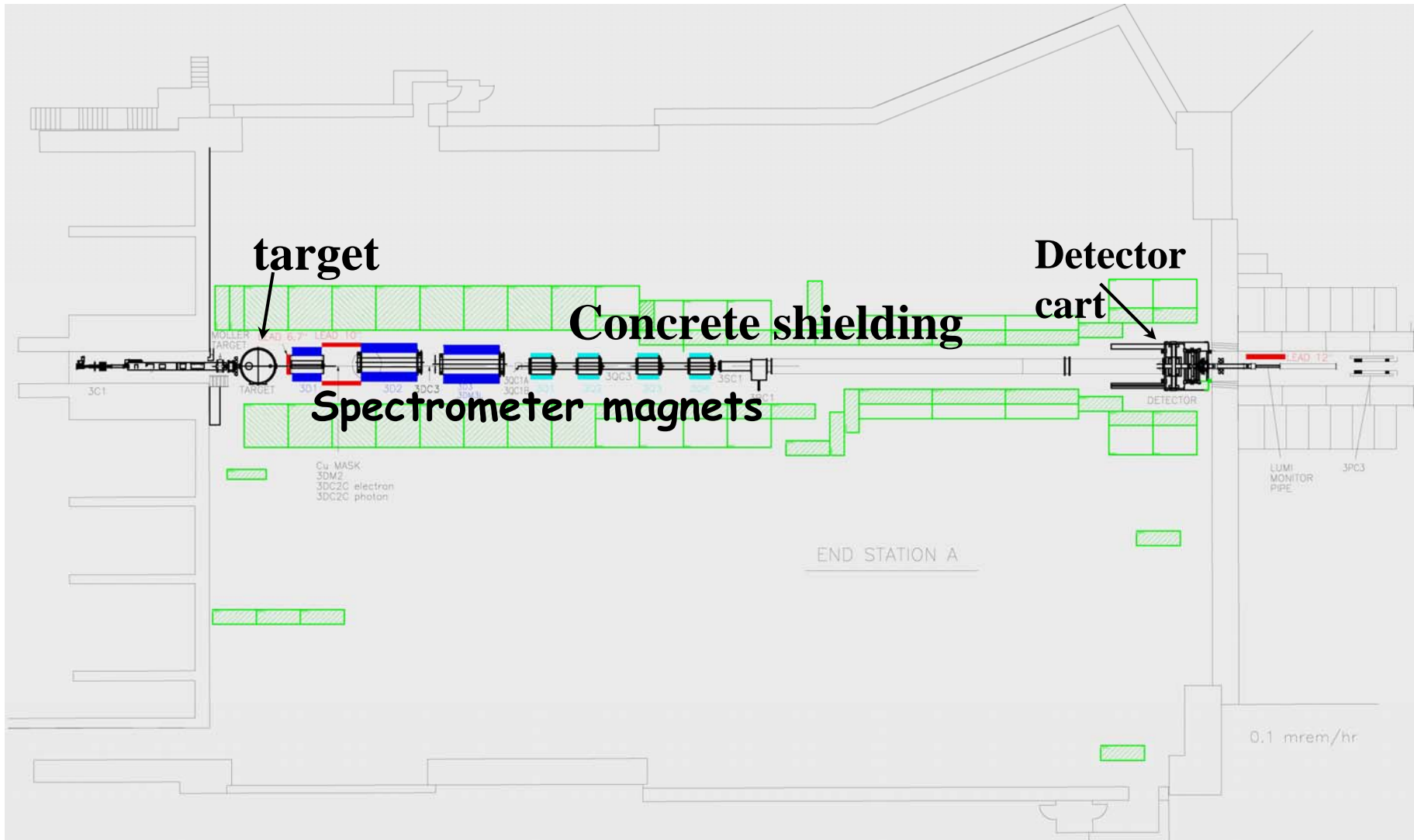
→ jitter vs. statistics

III. Beam systematics

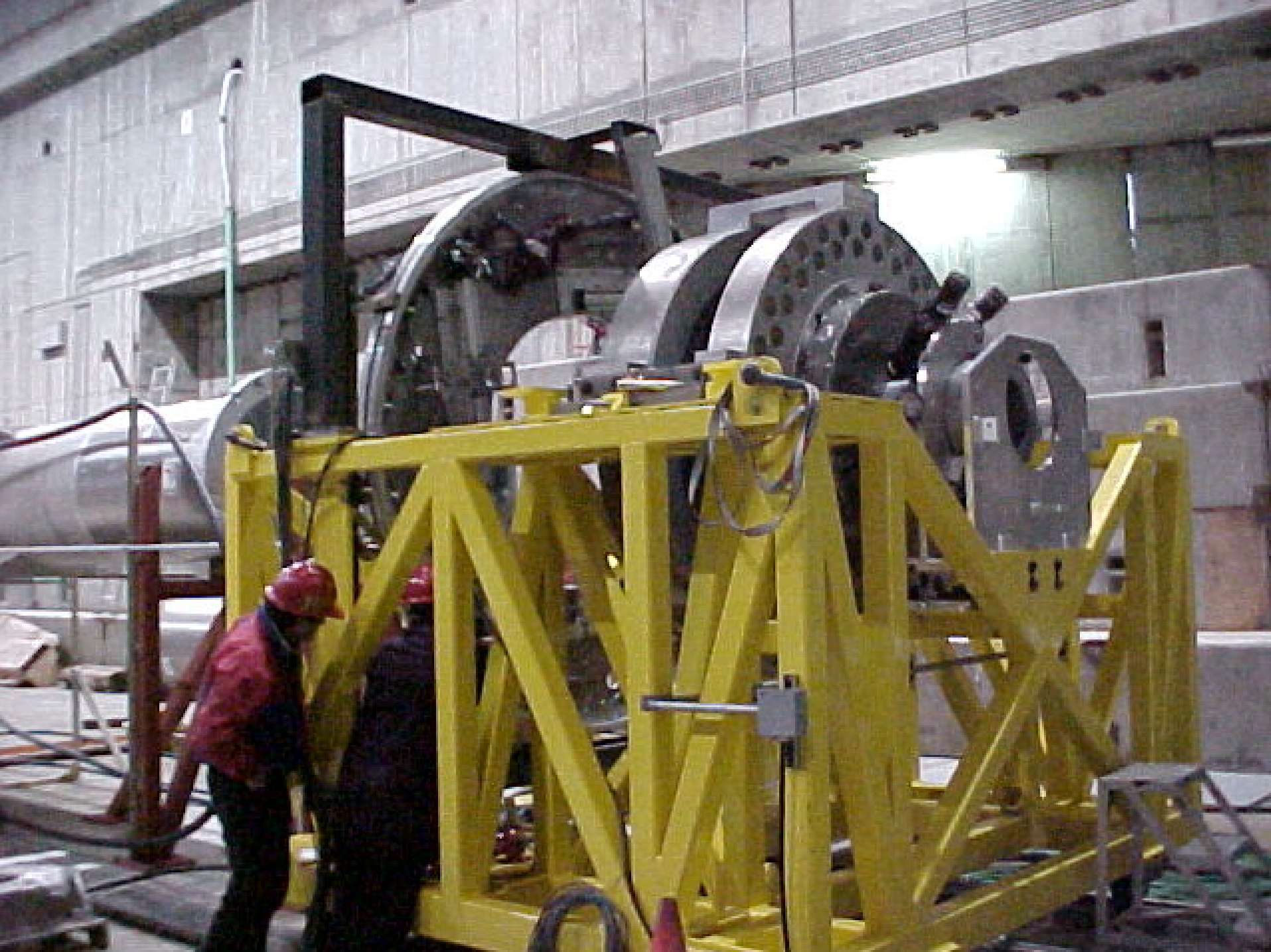
→ false asymmetries

IV. Backgrounds

Setup in End Station A





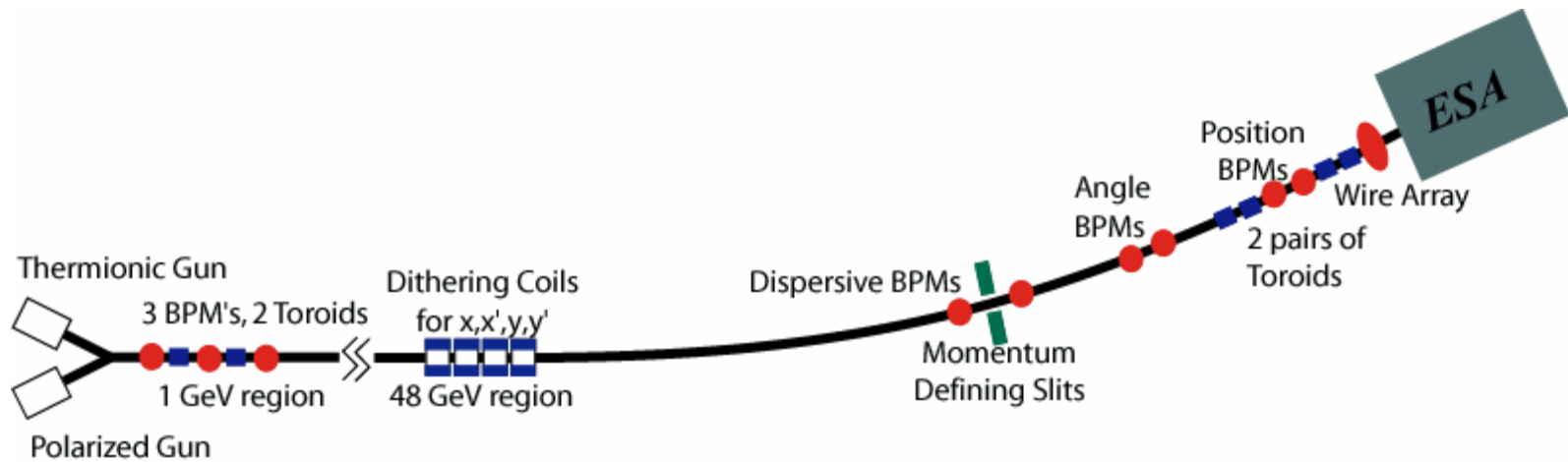


STATISTICS

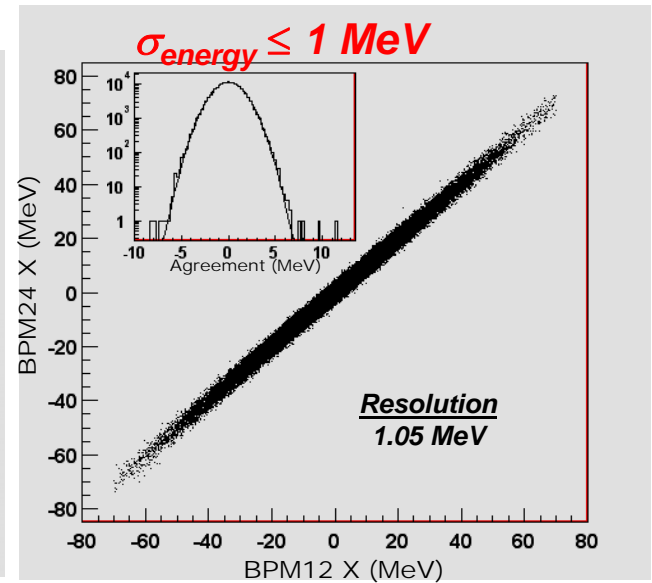
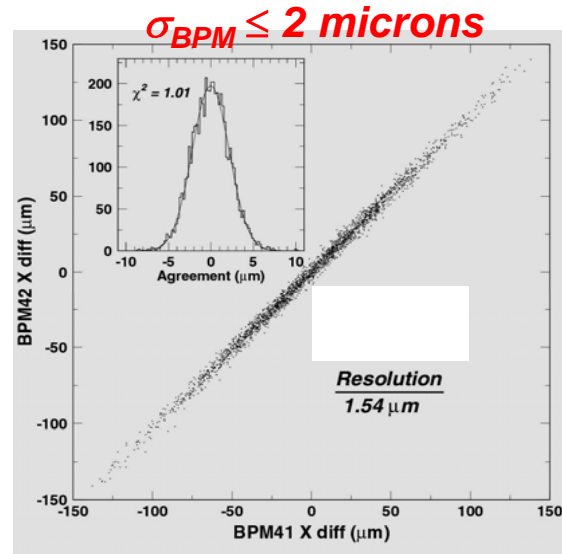
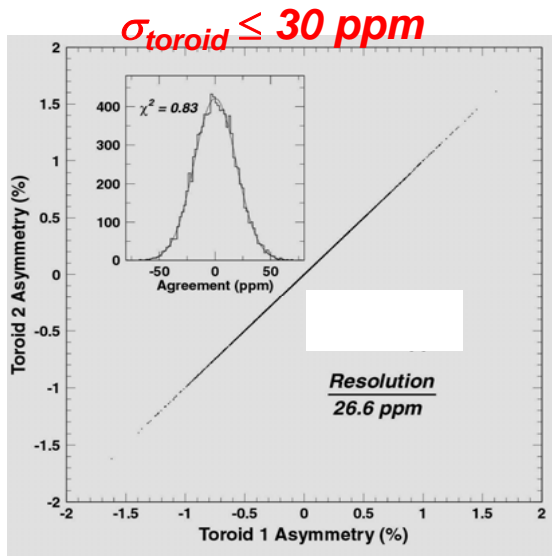
| | |
|-----------------------|-----------|
| # electrons per pulse | 10^7 |
| Rep rate (120 Hz) | 10^9 |
| Seconds/day | 10^{14} |
| 100 days | 10^{16} |

$$\Delta A \sim 10^{-8}$$

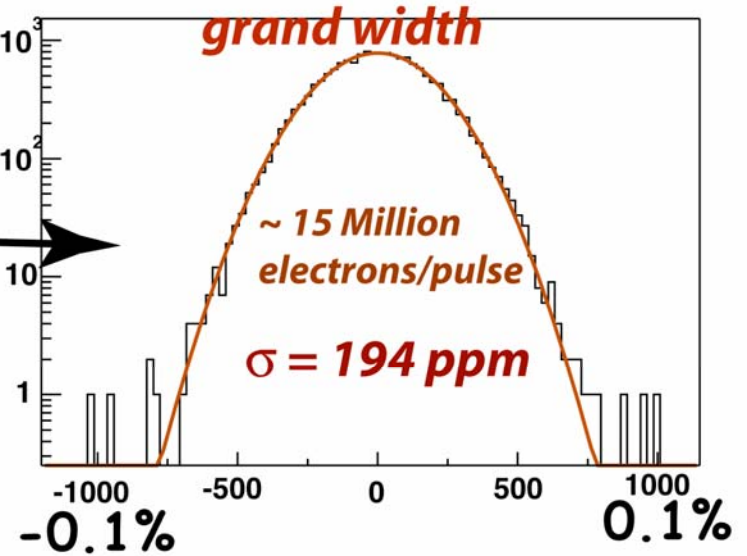
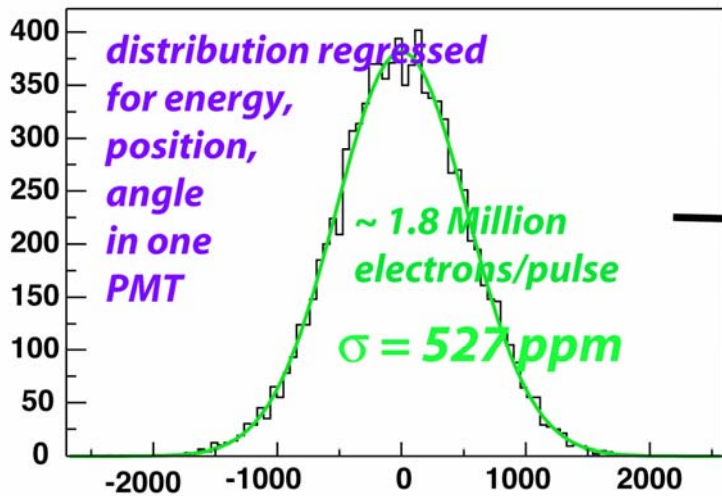
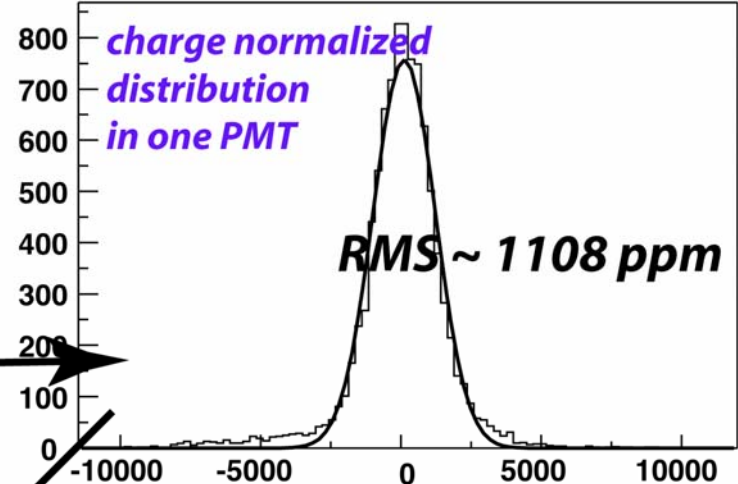
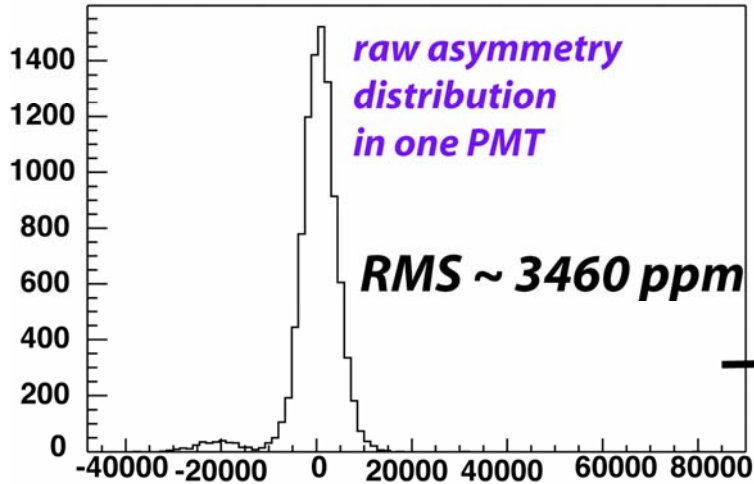
II. BEAM MONITORING



Beam Monitoring Correlations

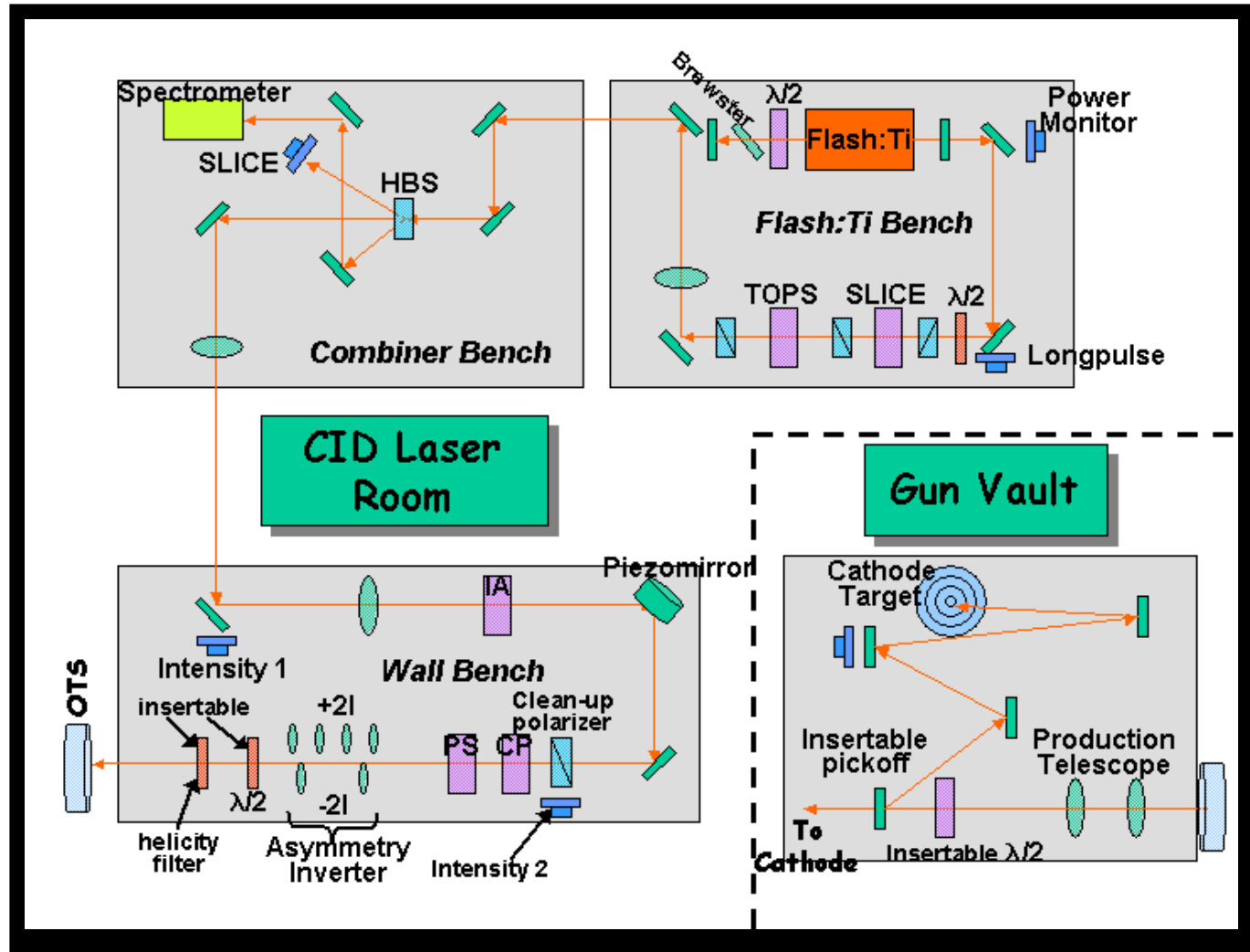


observed left-right asymmetry distribution



III. Beam Asymmetries

Polarized source



SLOW REVERSALS

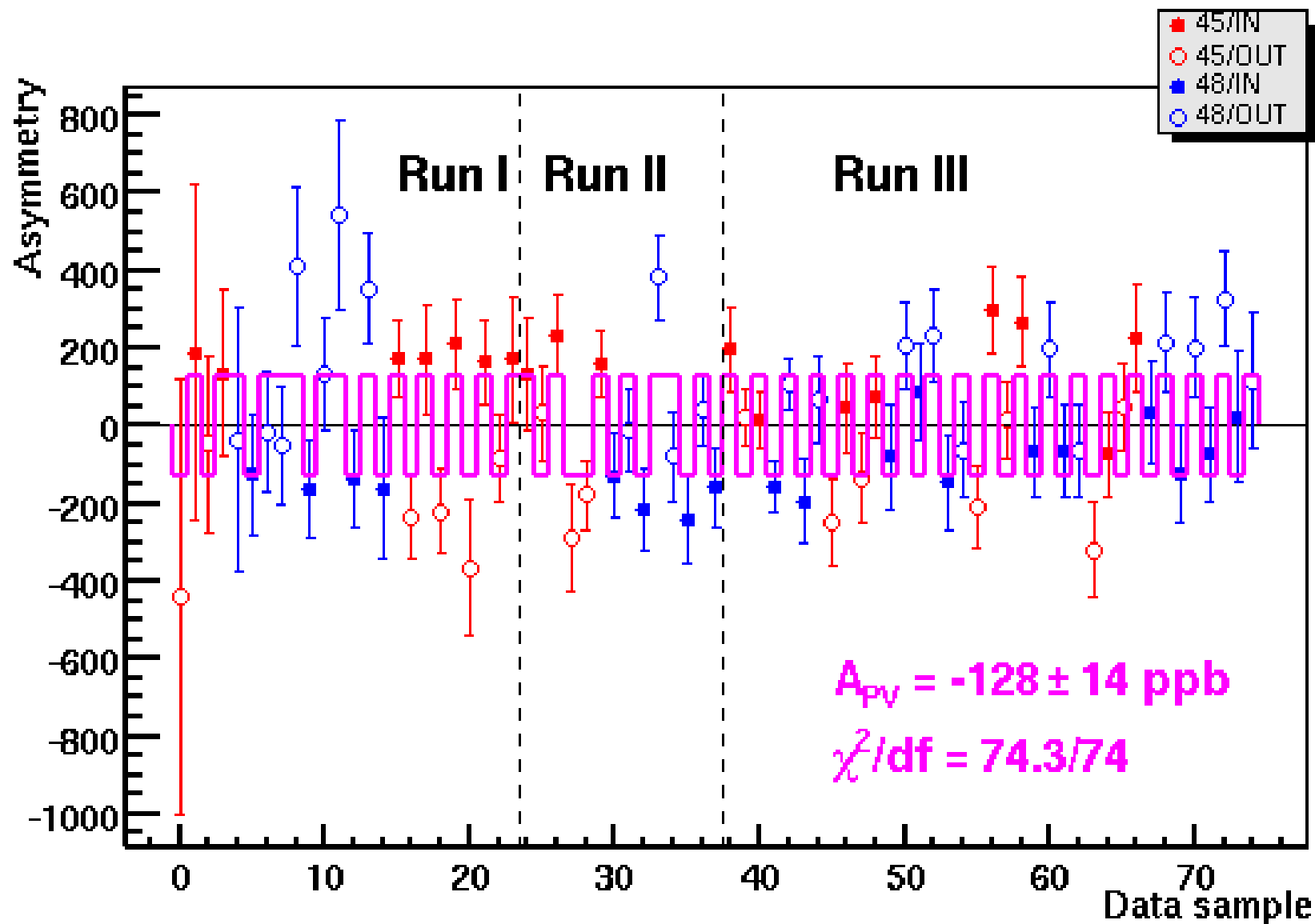
- * Halfwaveplate @ source

~few hours

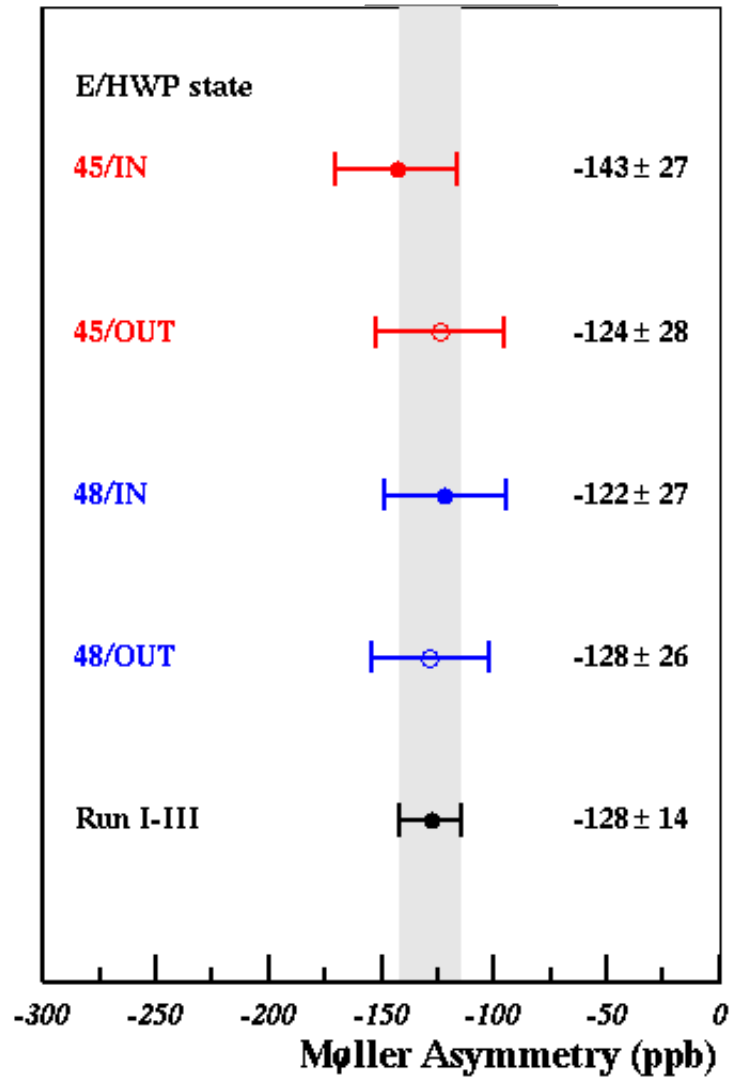
- * 48 vs. 45 GeV energy

~ few days

A^{PV} vs. time



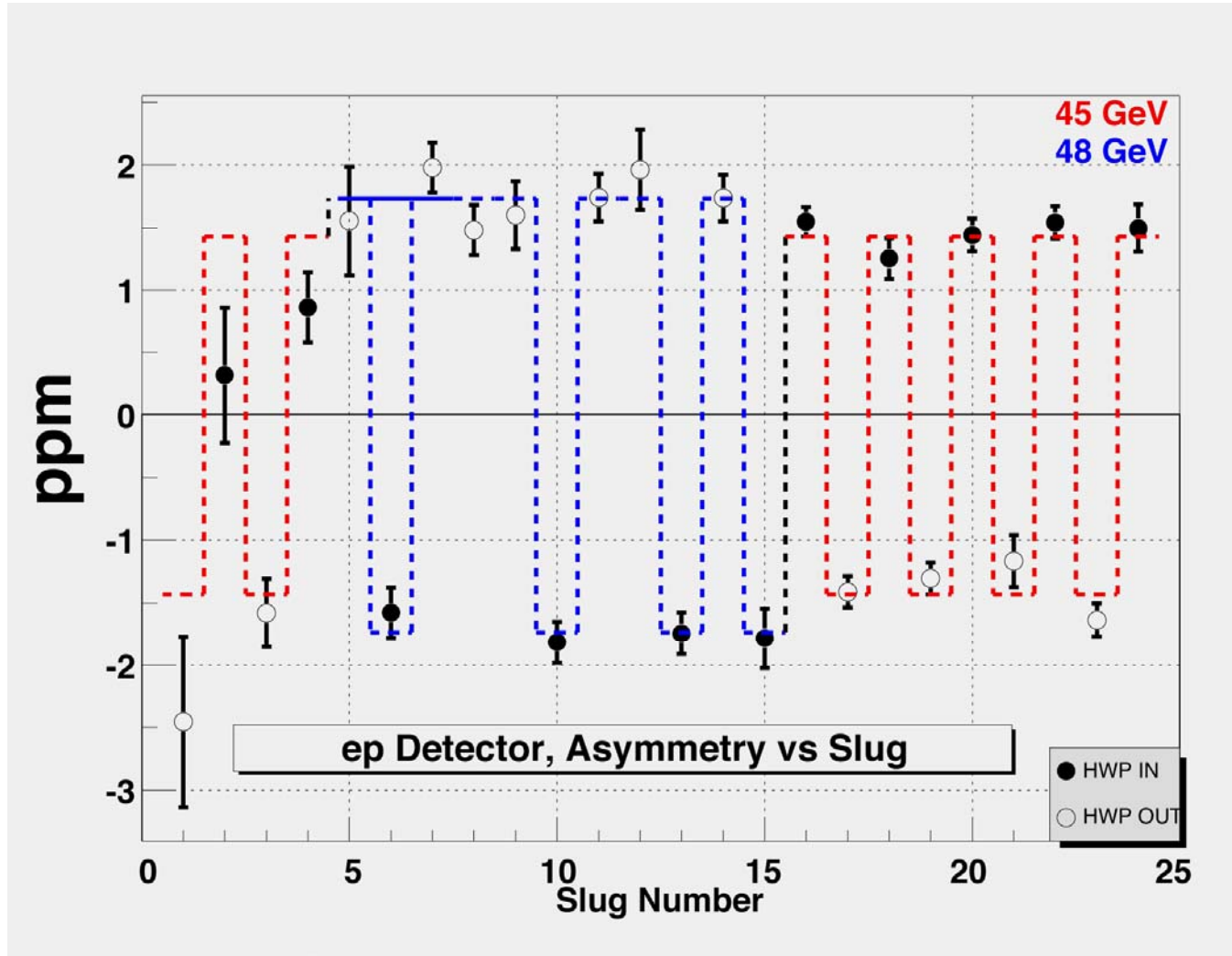
Asymmetry Results



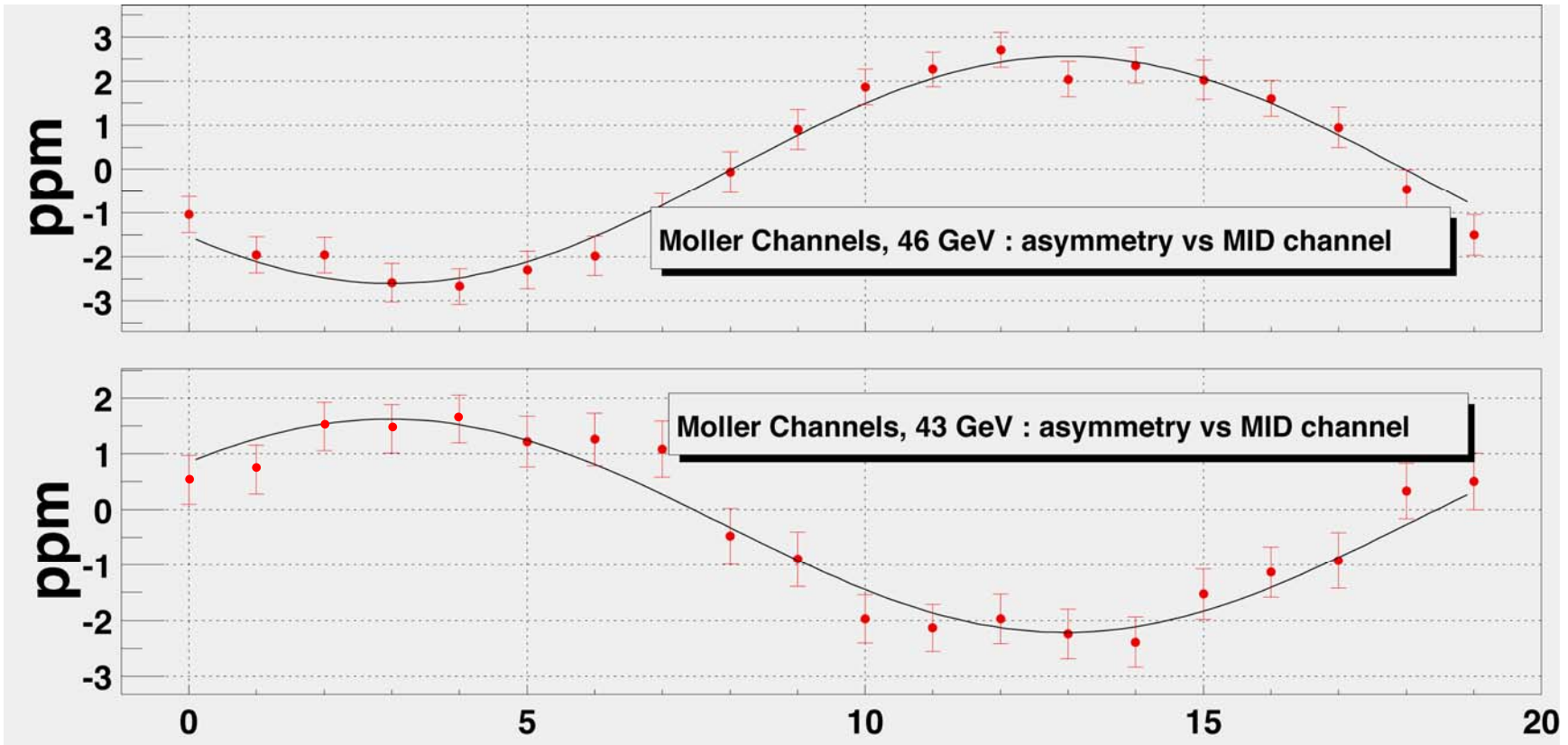
IV. BACKGROUNDS

- * electron-proton elastic scattering
- * pion production
- * radiative inelastic electron-proton scattering
 $W^2 > 3 \text{ GeV}^2$
- * 2 photon events with transverse polarization
 - *
 - *
 - *

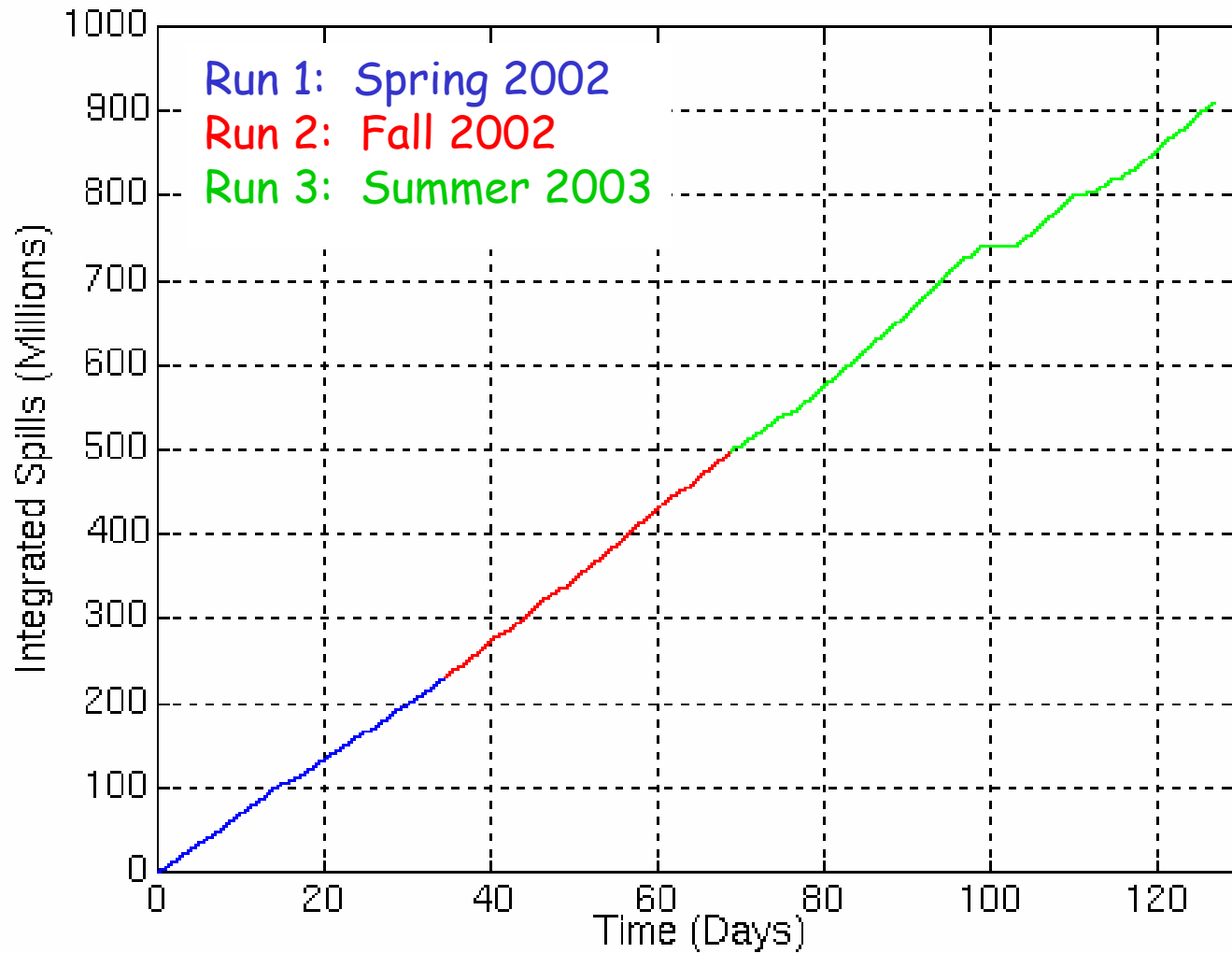
ep Detector Asymmetry



Transversely Polarized Beam



E158 Physics Runs

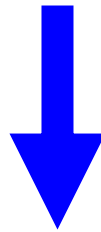


RUN I

FINAL RESULT

At $Q^2 = 0.027 \text{ (GeV/c)}^2 \dots$

$$A^{PV} = -175 \pm 30 \text{ (stat)} \pm 20 \text{ (syst) ppb}$$



$$\sin^2 \theta_w^{\overline{MS}} = 0.2293 \pm 0.0024 \text{ (stat)} \pm 0.0016 \text{ (syst)}$$

Theory: $\sin^2 \theta_w^{\overline{MS}} = 0.2311 \pm 0.00016$

Observation of Parity Nonconservation in Møller Scattering

P. L. Anthony,⁷ R. G. Arnold,³ C. Arroyo,³ K. Baird,⁷ K. Bega,² J. Biesiada,^{1,4} P. E. Bosted,³ M. Breuer,³ R. Carr,² G. D. Cates,¹⁰ J.-P. Chen,⁹ E. Chudakov,⁹ M. Cooke,¹ F. J. Decker,⁷ P. Decowski,⁶ A. Deur,¹⁰ W. Emam,⁸ R. Erickson,⁷ T. Fieguth,⁷ C. Field,⁷ J. Gao,² K. Gustafsson,^{2,*} R. S. Hicks,³ R. Holmes,⁸ E. W. Hughes,² T. B. Humensky,⁴ G. M. Jones,² L. J. Kaufman,³ Yu. G. Kolomensky,¹ K. S. Kumar,³ D. Lhuillier,⁵ R. Lombard-Nelsen,⁵ P. Mastromarino,² B. Mayer,⁵ R. D. McKeown,² R. Michaels,⁹ M. Olson,⁷ K. D. Paschke,³ G. A. Peterson,³ R. Pitthan,⁷ K. Pope,^{6,†} D. Relyea,^{4,7} S. E. Rock,³ O. Saxton,⁷ G. Shapiro,^{1,†} J. Singh,¹⁰ P. A. Souder,⁸ Z. M. Szalata,⁷ W. A. Tobias,¹⁰ B. T. Tonguc,⁸ J. Turner,⁷ B. Tweedie,¹ A. Vacheret,⁵ D. Walz,⁷ T. Weber,⁷ J. Weisend,⁷ D. Whittum,⁷ M. Woods,⁷ and I. Younus⁸

(SLAC E158 Collaboration)

¹*University of California, Berkeley, California 94720, USA*

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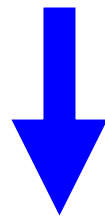
(Received 11 December 2003; published 7 May 2004)

All E158 Data

PRELIMINARY

At $Q^2 = 0.027 \text{ (GeV/c)}^2 \dots$

$$A^{PV} = -128 \pm 14 \text{ (stat)} \pm 12 \text{ (syst) ppb}$$

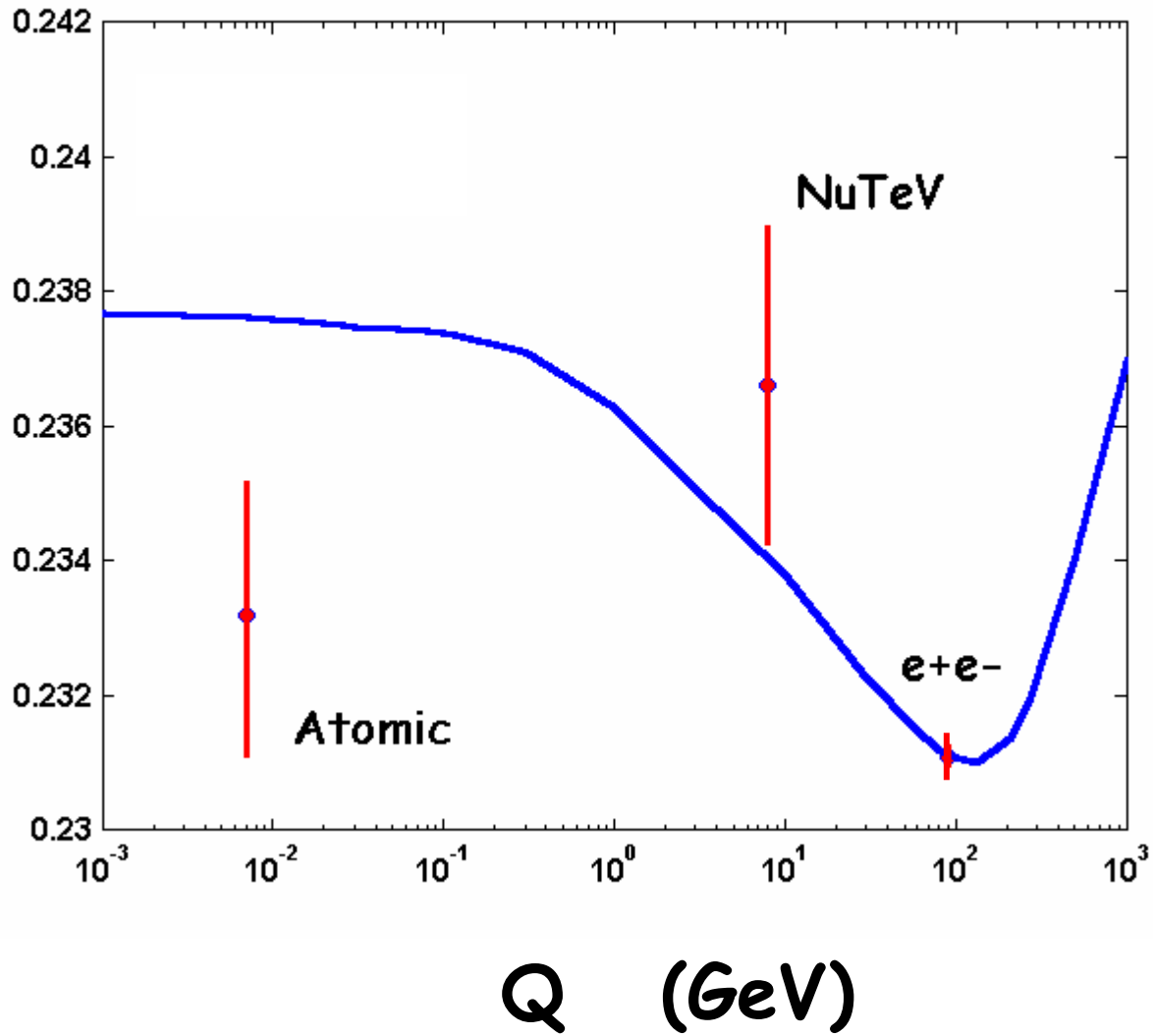


$$\sin^2 \theta_w^{\overline{MS}} = 0.2330 \pm 0.0011 \text{ (stat)} \pm 0.0010 \text{ (syst)}$$

Theory: $\sin^2 \theta_w^{\overline{MS}} = 0.2311 \pm 0.00016$

Status in 1999

$\sin^2\theta_w$



Precise Determination of Electroweak Parameters in Neutrino-Nucleon Scattering

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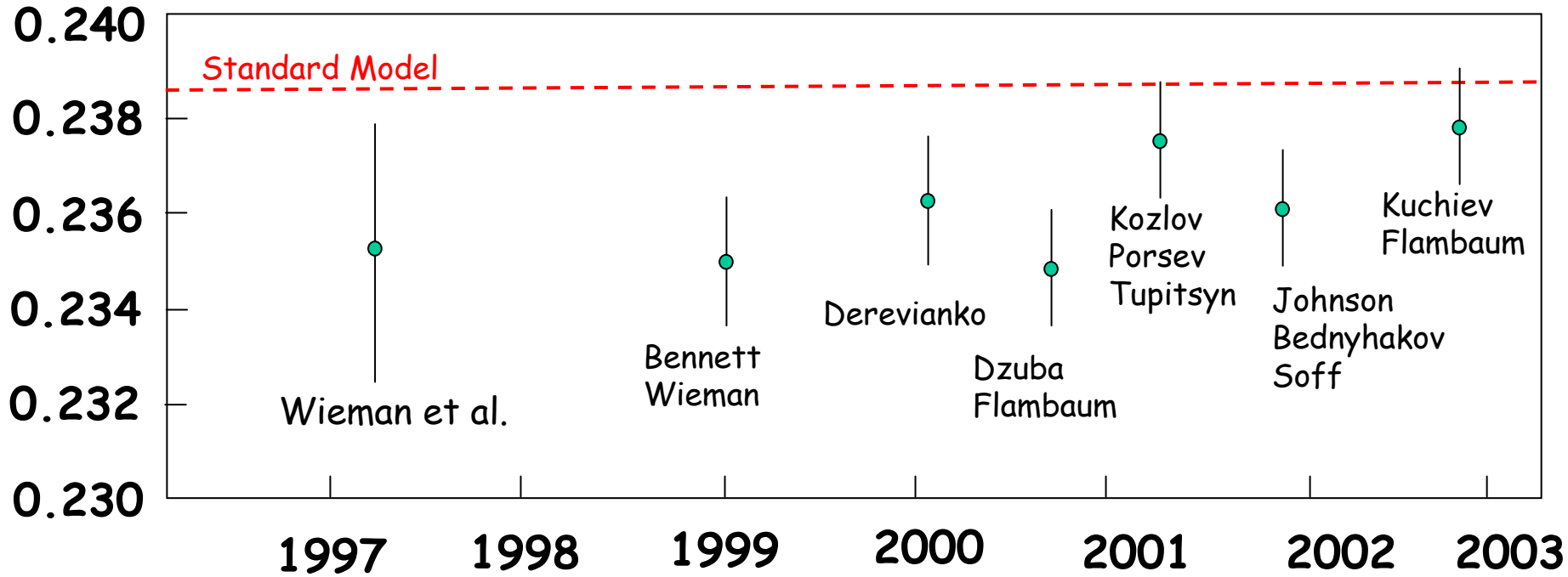
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(Received 25 October 2001; published 12 February 2002)

The NuTeV Collaboration has extracted the electroweak parameter $\sin^2\theta_W$ from the measurement of the ratios of neutral current to charged current ν and $\bar{\nu}$ cross sections. Our value, $\sin^2\theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$, is 3 standard deviations above the standard model prediction. We also present a model independent analysis of the same data in terms of neutral-current quark couplings.

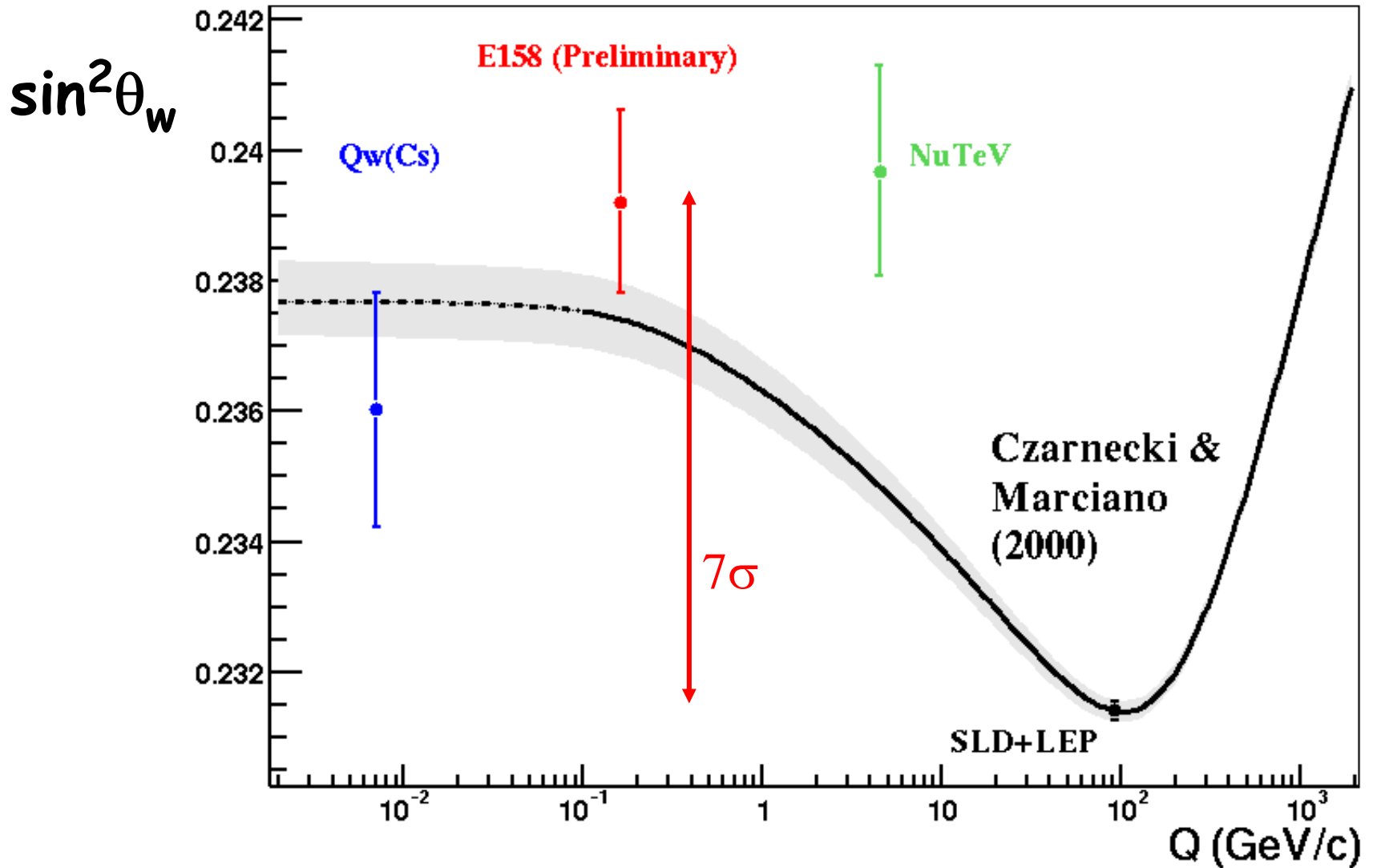
Cesium Atomic Parity Violation Result vs. Time (Colorado measurement)

$\sin^2\theta_w$



Modifications in the theoretical corrections to the
atomic structure

Status Today



E158 Beyond Standard Model Implications...

(95% confidence level)

- * Limit on $\Lambda_{LL} \sim 10 \text{ TeV}$
- * Limit on $SO(10) \text{ } Z' \sim 900 \text{ GeV}$
- * Limit on lepton flavor violating coupling $\sim 0.01 G_F$

FUTURE:

Low energy polarized electron scattering

- * **Jefferson Lab**
- * **SLAC** (could do it, but won't)

The Qweak Experiment:

A Search for New Physics at the TeV Scale Via a Measurement of the Proton's Weak Charge

December 3, 2001

Approved January 2002

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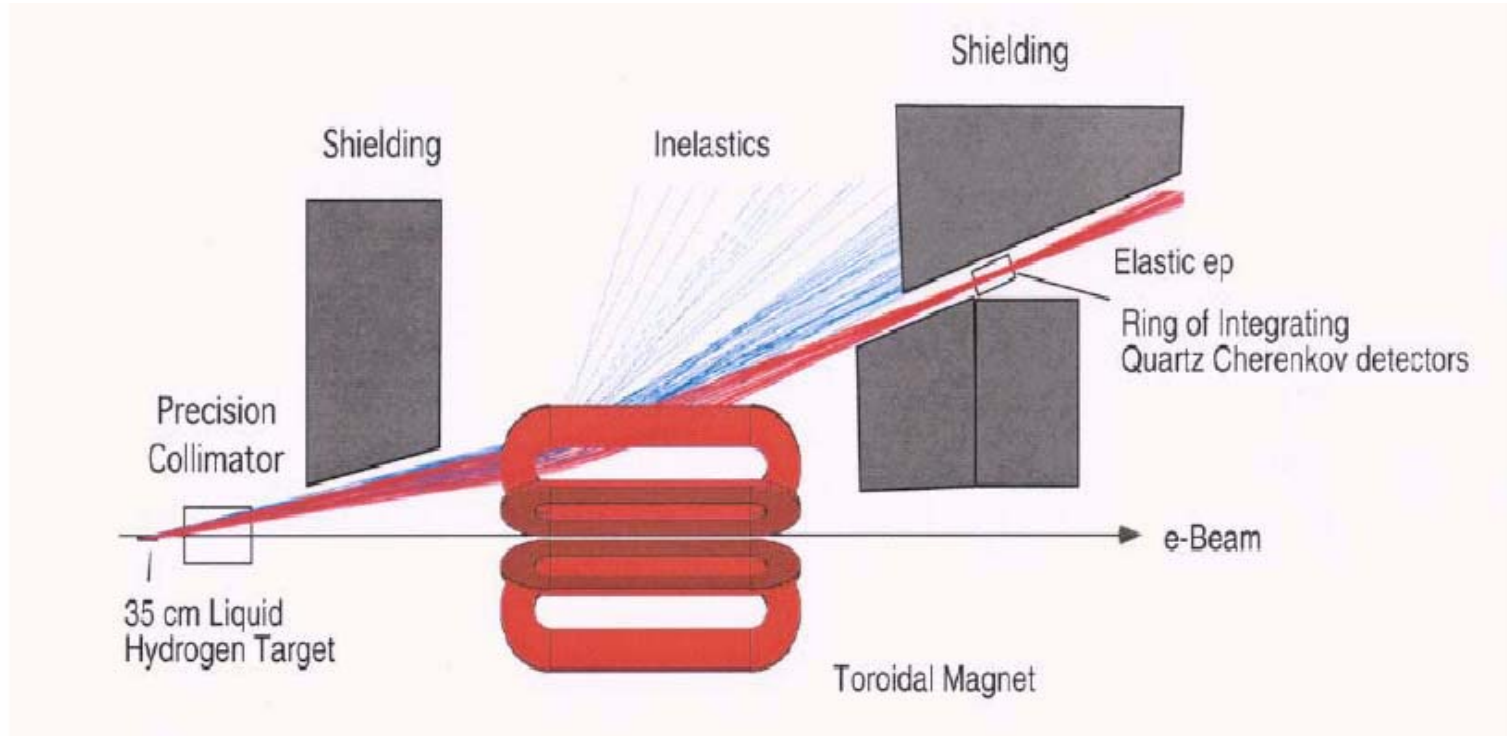
9 TJNAF, Newport News, VA

10 Virginia Polytechnic Institute, Blacksburg, Virginia

11 TRIUMF, Vancouver, Canada

Jefferson Lab Qweak Experiment

Elastic electron-proton scattering experiment

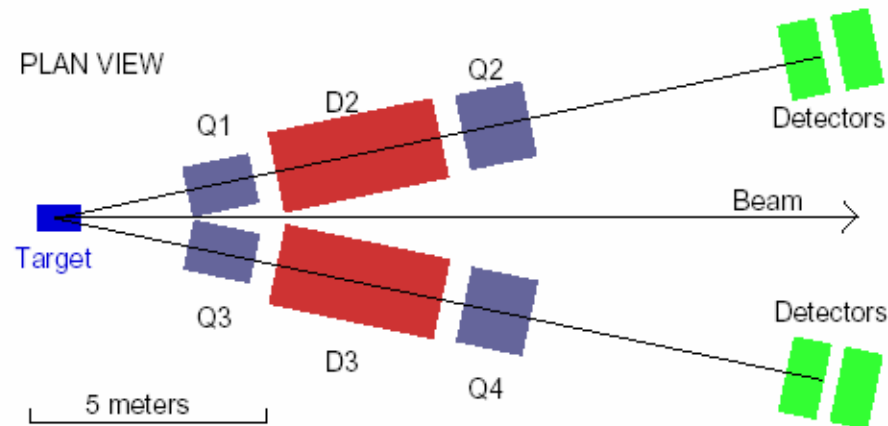


- * 180 μ Amp current
- * 1 GeV beam
- * 2200 hours of data

Submitted: June 2003

SLAC DIS-Parity Letter of Intent

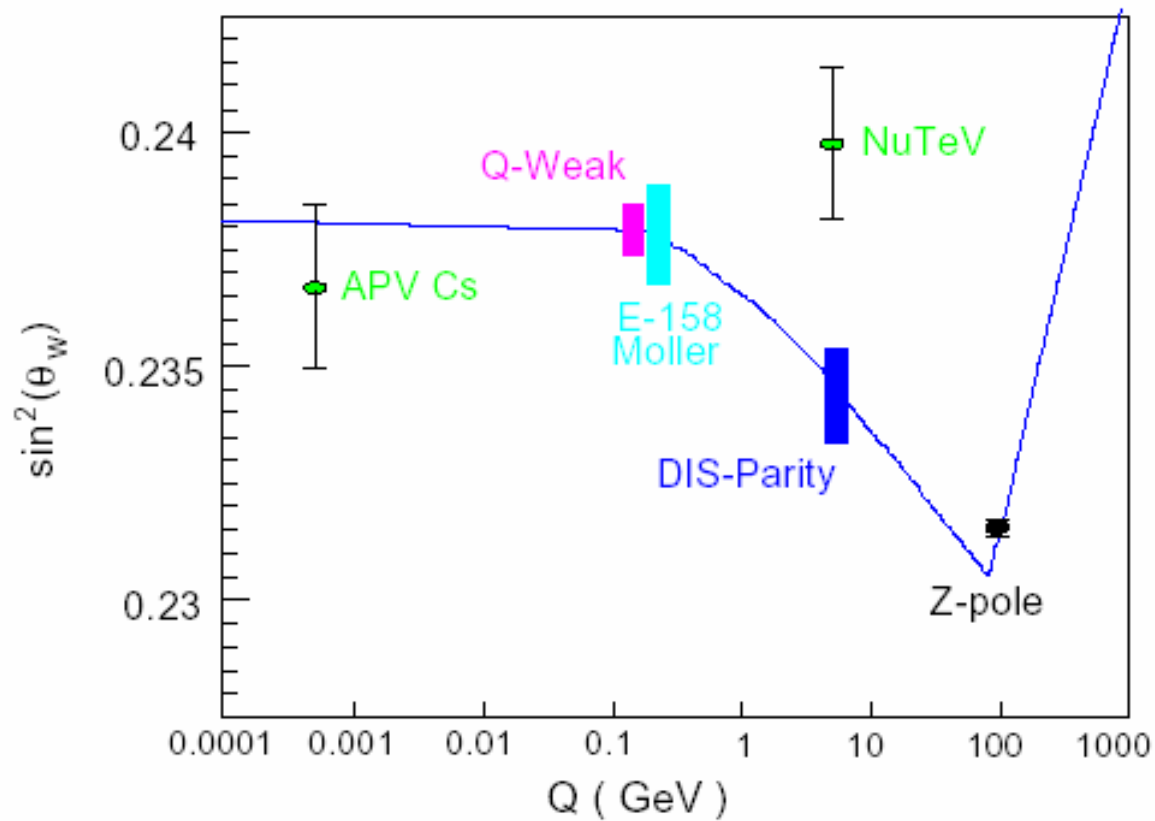
~39 GeV polarized electrons scattering off deuterium target



$$A^{LR} \sim 10^{-3} \text{ at } Q^2 \sim 20 \text{ GeV}^2$$

Measurement to 0.6% precision...

Projected experimental uncertainty from **DIS-parity** proposal @ SLAC and **Qweak** experiment @ Jefferson Lab



LHC

Not a parity experiment ...

→ Has major impact on precision low energy tests for discovery potential

Z', supersymmetry, compositeness, leptoquarks, etc...

in the TeV range

SUMMARY

- * Performed a first measurement of parity violation in e^-e^- scattering

Final result publication in $\sim 1/2$ year

- * Future parity experiments active
- * Complementary to collider experiments