The Physics of Electron-Electron (Møller) Scattering:

A narrative: from the 1920s to PAC 34

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January 23, 2009

Outline

- *Historical Perspective*
- *Parity-Violating Electron Scattering*
- *E158 at SLAC*
- *A Potential 11 GeV Experiment*

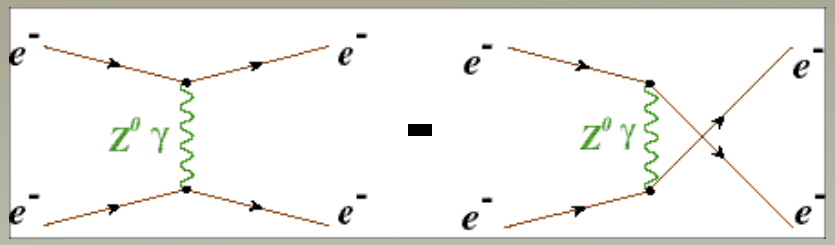
Birth of Quantum Electrodynamics

- *QED was born with the 1927 publication of Dirac's quantum theory of radiation*
- *Dirac equation published in 1928*
  - quantized radiation field coupling with Dirac fermions
  - interaction of light with relativistic electrons
  - electron spin, g factor, hydrogen fine structure...
- *Important results*
  - Klein-Nishina: scattering of light by electrons
  - electron bremsstrahlung
  - relativistic electron-electron scattering: Møller formula

Relativistic Electron Scattering

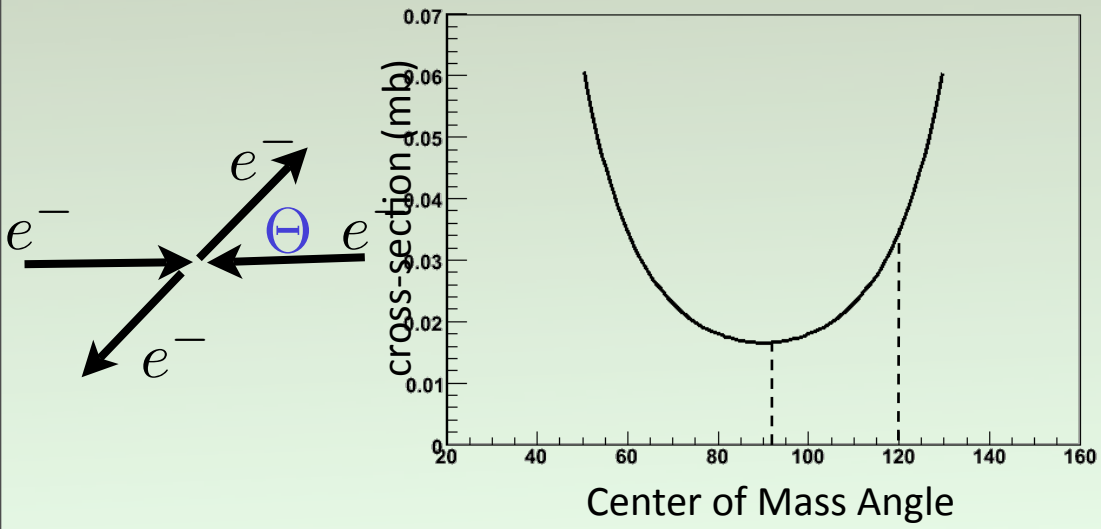
- *Mott Scattering*
  - In 1932, British physicist Neville Mott published the relativistic scattering formula for electrons off nuclei; predicted electron polarization after scattering
- *Bhabha Scattering*
  - In the 1930s, Indian physicist Homi Bhabha, working with Heitler, calculated electron-positron scattering and applied it to cosmic ray cascade showers
  - In electron-positron collider physics, the jargon is still to talk about detecting "Bhabha's" in forward calorimeters for measuring absolute luminosity
- *Møller Scattering*
  - In the late 20's, Danish physicist Christian Møller calculated relativistic electron-electron scattering

Møller Scattering



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

- ***Møller's first calculation was relativistic but did not use quantized fields***
- ***In 1932, he published the calculation of electron energy loss; basis for experimental investigation of cosmic rays that led to discoveries of the positron and the muon***



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

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

Test of QED ~ 1 GeV

mid-60's

A TEST OF QUANTUM ELECTRODYNAMICS BY ELECTRON-ELECTRON SCATTERING*

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

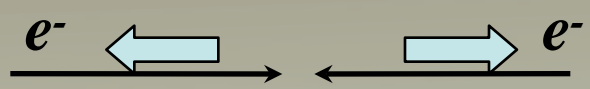
Stanford University

We have measured the differential cross-section for electron-electron scattering at a total energy of 600 MeV in the center-of-mass system, by a colliding-beam technique using storage rings[1,2,3]. This

- *In the mid-1960s, QED validity was being probed at ~ 10^{-15} m*
- *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; had to include radiative corrections*
- *A good example of a technical advancement for a parallel goal (colliders were after new particles) that used a different physics topic as an intermediate goal to justify activity*

Polarized Møller Scattering

mid-70s



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

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Stanford Linear Accelerator Center, Stanford, CA. 94305

- *birth of high energy spin physics*
- *the first polarized electron source*
- *polarized target electrons: Fe foil*
- *Large cross-section; well-known double-spin asymmetry*

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

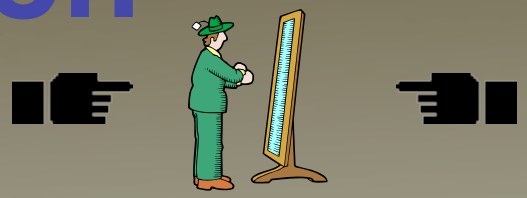
ABSTRACT

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

Parity Violation

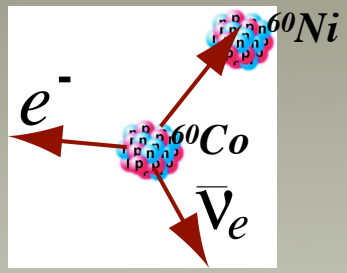
parity transformation (reflection)

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

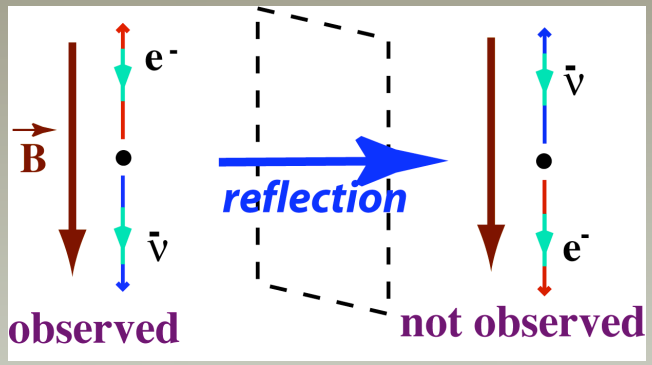


$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{s} \rightarrow \vec{s}$$

Discovery of Parity Violation (late 1950s)



Weak decay of ^{60}Co Nucleus



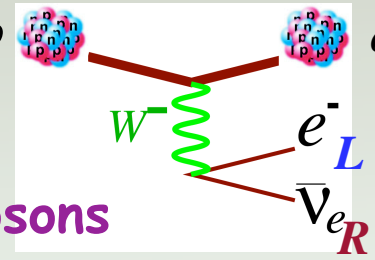
matter particles have spin = 1/2

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

handedness or
helicity/chirality

Mirror reflection flips sign of helicity

Left-handed ⟺ ***right-handed***



right-handed anti-neutrino

Only left-handed particles can exchange 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)

Parity Violation in Electron Scattering?

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

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

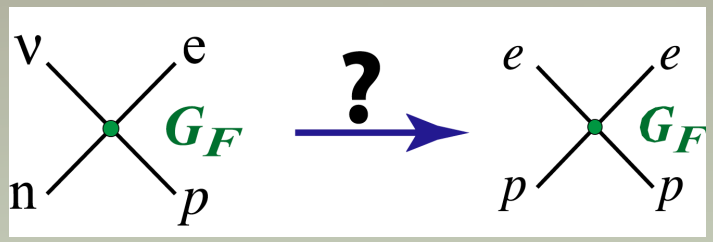
with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1+i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

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 β Decay

Electron-proton Weak Scattering

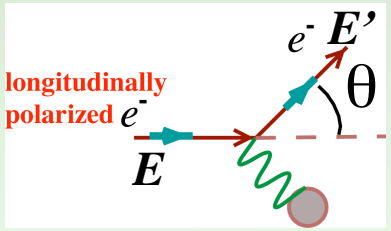


$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

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

Parity-violating

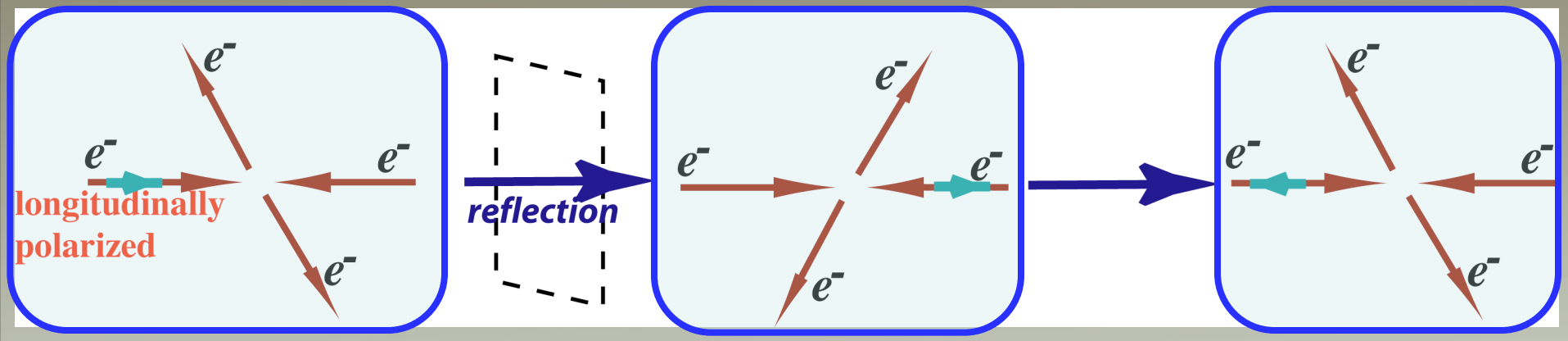
$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = -A_{LR}$$



4-momentum transfer

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

Observable Parity-Violating Asymmetry



- *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 non-conservation effects can be of the order of 0.1 to 0.01 percent.

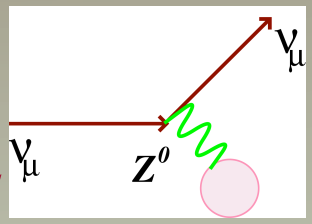
$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

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

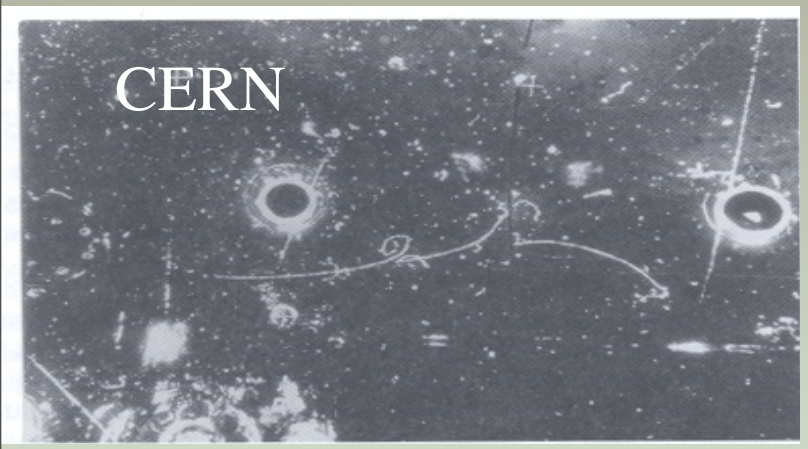
Neutral Weak Interaction Theory

A Model of Leptons

Steve Weinberg - 1967



The Z boson incorporated



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

The weak mixing angle introduced

Gargamelle finds one ν_μ e^- event in 1973!
(two more by 1976)

electron-nucleon scattering

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

Weinberg model

Parity is violated

or

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

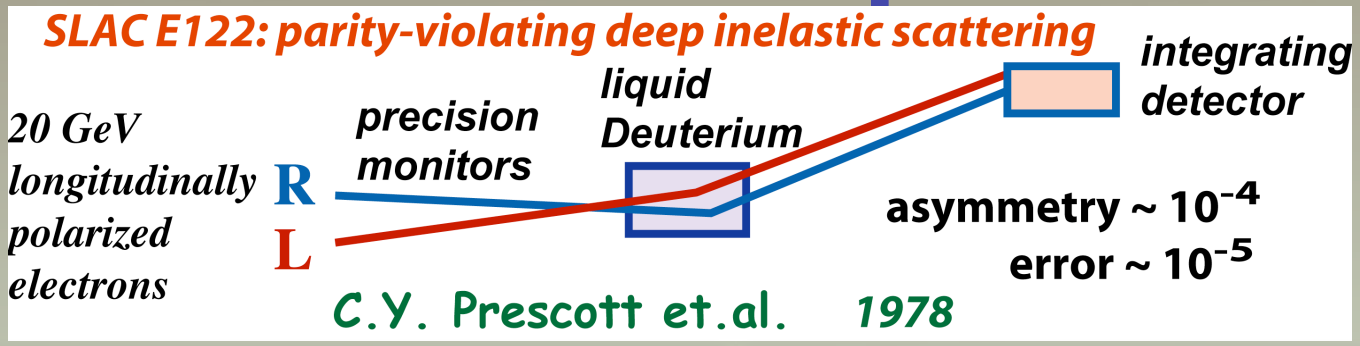
Parity is conserved

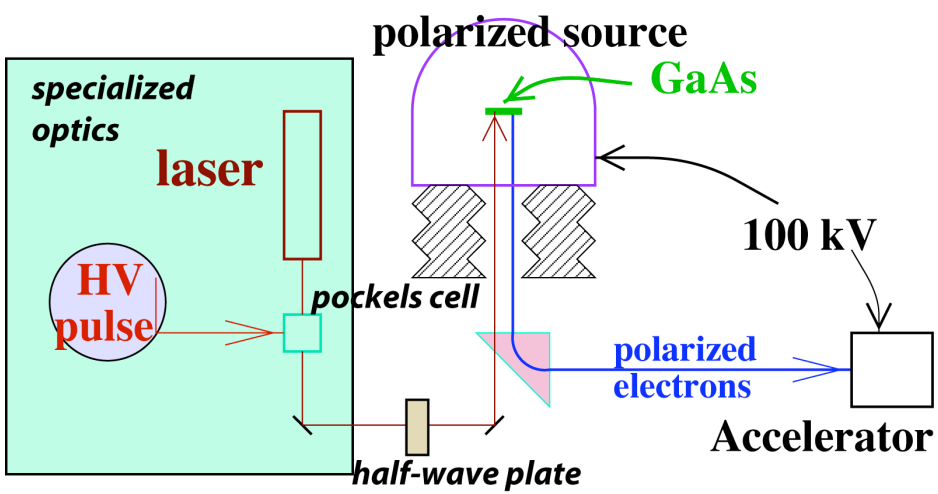
Landmark experiment (late 1970s)

at Stanford Linear Accelerator Center (SLAC)

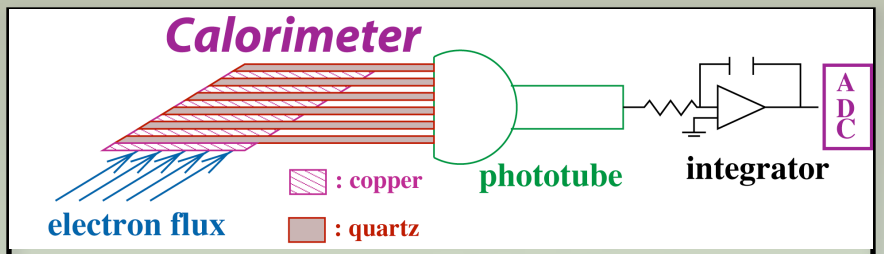
***E122** at SLAC demonstrated parity-violation in electron-nucleon deep inelastic scattering*

SLAC E122 Experiment





- Optical pumping of a GaAs wafer
- Rapid helicity reversal: polarization sign flip ~ 100 Hz to minimize the impact of drifts
- Helicity-correlated beam motion: under sign flip, beam stability at the micron level



"Flux Integration":
Allows counting at high rates

Spectrometer directs flux to background-free region

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

Late 80's: achieved ~ 10^{-7}

- **Carbon target at MIT Bates**
- **Beryllium target at Mainz**

Beyond the Standard Model

Since the late 80's...

High Energy Colliders *SLC, LEP, LEPII, HERA, Tevatron, PEPII, LHC…*

- New Particle Searches
- Rare or Forbidden Processes
- Symmetry Violations
- Electroweak One-Loop Effects

→ *Complementary Approaches*

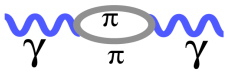
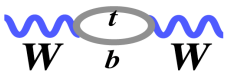
Low Energy: $Q^2 << M_Z^2$

Low Q^2 offers unique and complementary probes of "new physics"

- Rare or Forbidden Processes — *neutrinoless double-beta decay…*
- Symmetry Violations — *Neutrino oscillations, EDM searches…*
- **Indirect Effects of "New Physics"**

g-2 anomaly, CKM Unitarity *weak neutral current interactions (WNC)*

Precision WNC Measurements

α_{QED} G_F   M_Z

σ_Z M_W A_f

- Precise predictions @ 0.1%
- Indirect access to TeV scale

Early 90's:

- *World electroweak data has marginal χ^2, but no discernable pattern*
- *Data used to put limits on energy scale of new physics effects*

- *Parity-conserving contact interactions probed at 10 TeV level*
- *Parity-violating contact interactions probed at 1 TeV level*

Low Energy: $Q^2 << M_Z^2$

$$A_X \propto \frac{1}{\ldots}$$

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\,G_F} \longrightarrow \boxed{\begin{array}{l}\delta(g)/g \sim 0.1 \\ \Lambda \sim 10\ TeV\end{array}}$$

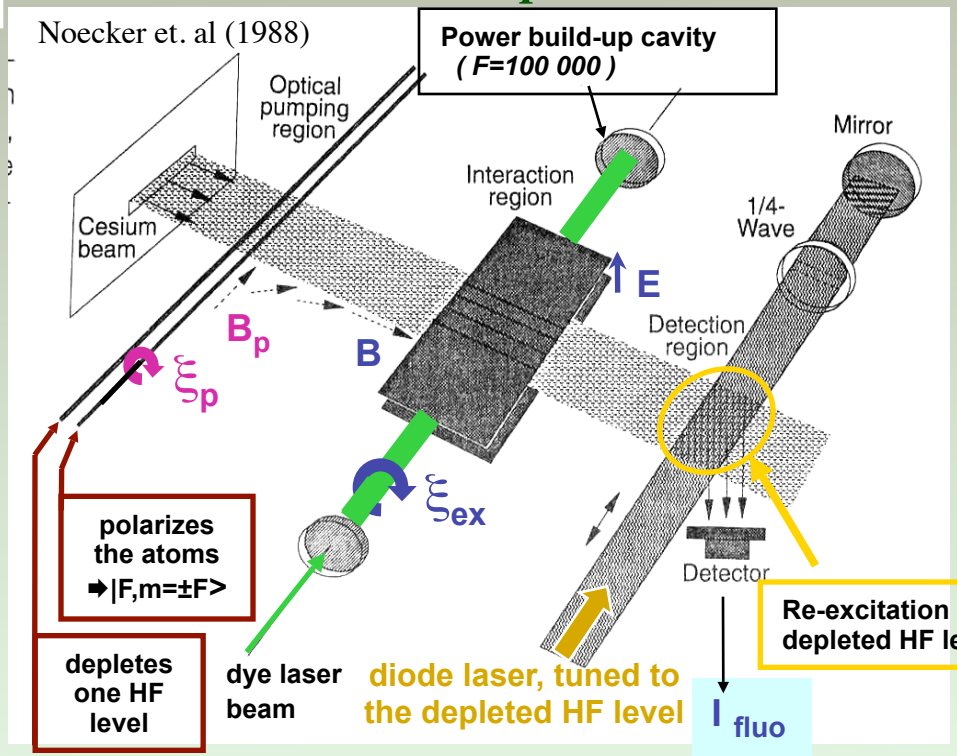
$$\frac{\delta(\sin\theta_W)}{\sin^2\theta_W} \lesssim 0.01$$

$Q^2 \sim M_Z^2$ **on resonance:** A_Z *imaginary* $\longrightarrow A_Z^2\left[1+\frac{A_X^2}{A_Z^2}\right]$ *no interference!*

Atomic Parity Violation

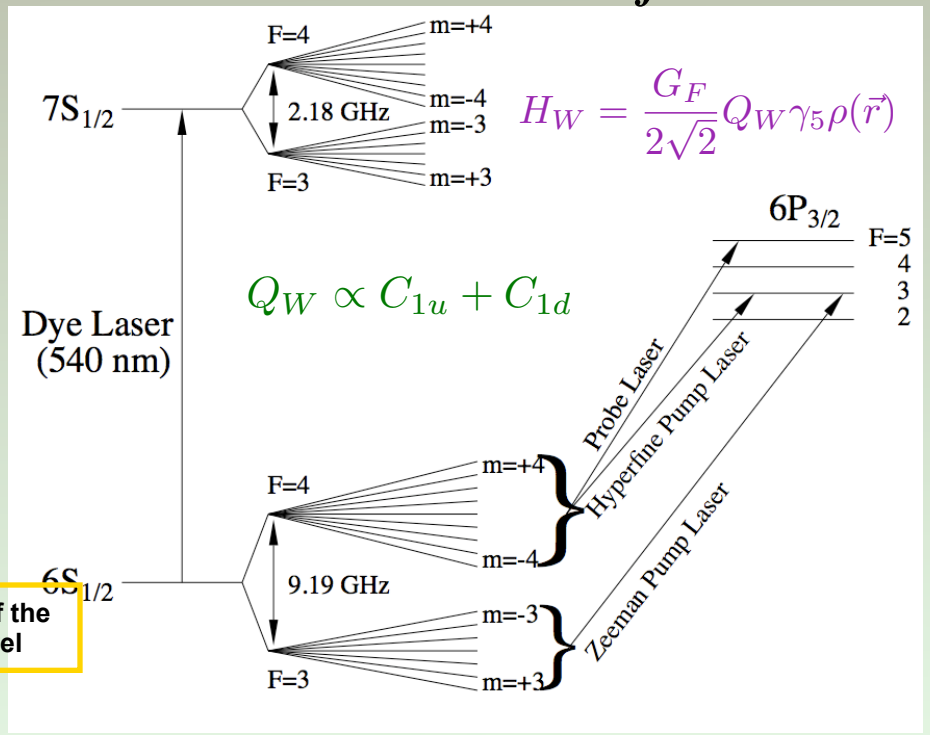
- *6S → 7S transition in ^{133}Cs is forbidden within QED*
- *Parity Violation introduces small opposite parity admixtures*
- *Induce an E1 Stark transition, measure E1-PV interference*
- *5 sign reversals to isolate APV signal and suppress systematics*
- *Signal is ~ 6 ppm, measured to 40 ppb*

Boulder Experiment



APV signal: odd in E, ξ_{ex}, B, B_p, ξ_p

Partial Level Structure of Cesium



Anatomy of a SLAC Proposal

$$A_{PV} \approx -4 \times 10^{-9} \times E_{beam} \times P_{beam}$$

- *~ 10 ppb statistical error at highest E_{beam}*
- *~ 0.4% 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

E158 Collaboration &

Parity-Violating Left-Right Asymmetry In Fixed Target Møller Scattering

At the Stanford Linear Accelerator Center

Goal: error small enough to probe TeV scale physics

E158 Collaboration

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

8 Ph.D. Students

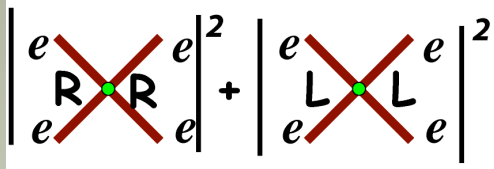
60 physicists

E158 Chronology

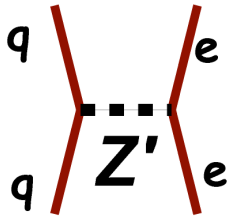
Feb 96: Workshop at Princeton
Sep 97: SLAC EPAC approval
Mar 98: First Laboratory Review
1999: Design and Beam tests
2000: Funding and construction
2001: Engineering run
2002-2003: Physics
2004: First PRL
2005: PRL on full statistics

E158 New Physics Reach

LEP II

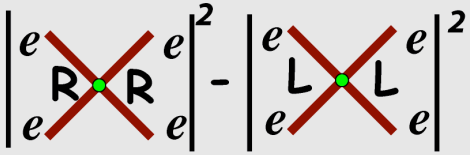


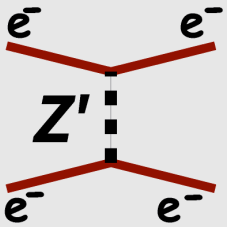
Fermilab

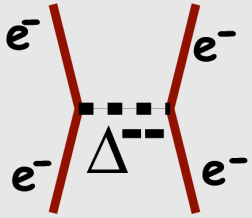


doubly charged scalar exchange

E158







15 TeV — compositeness

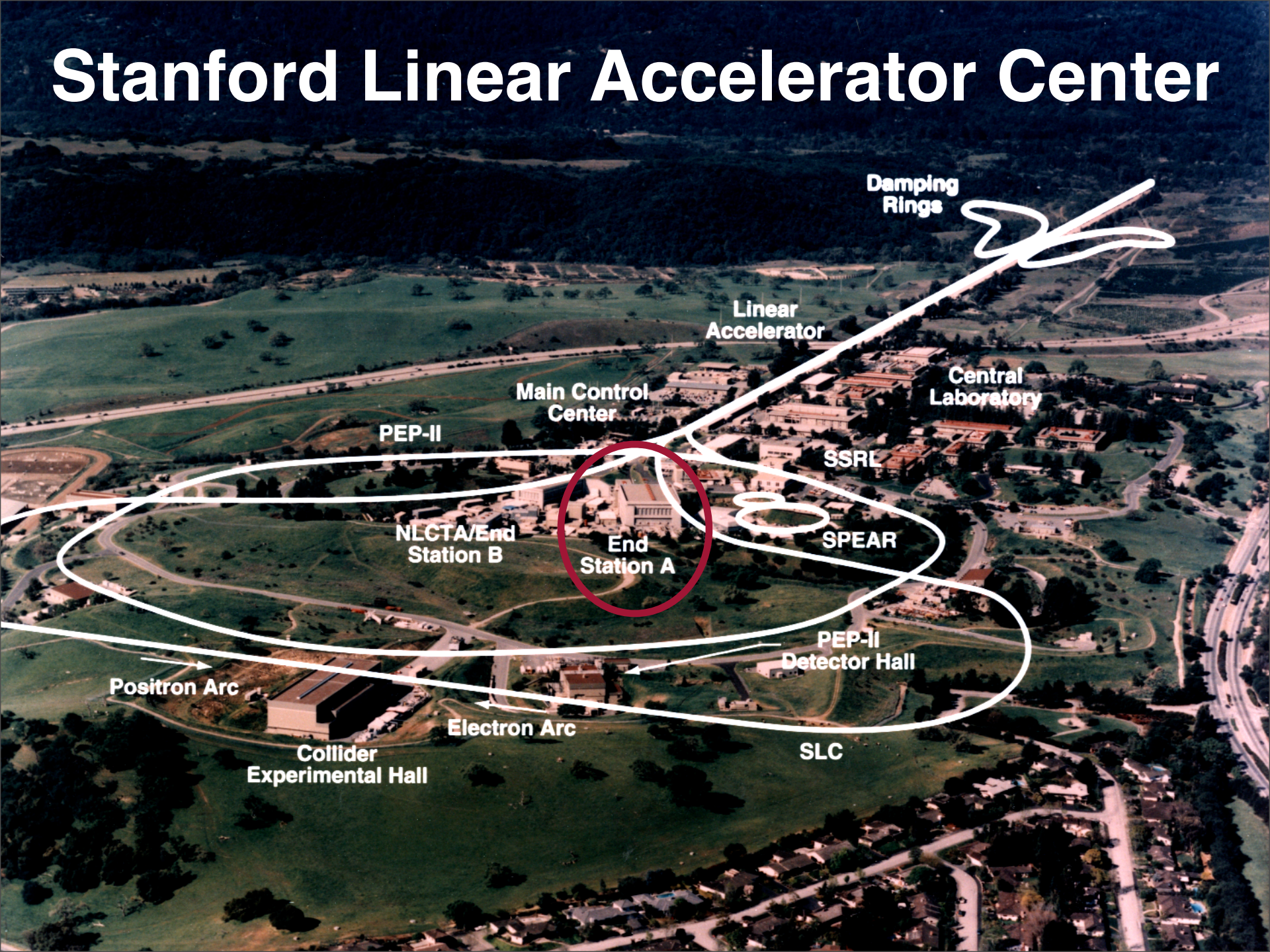
0.5-1.0 TeV — GUTs

0.5-2.5 TeV — extra dimensions

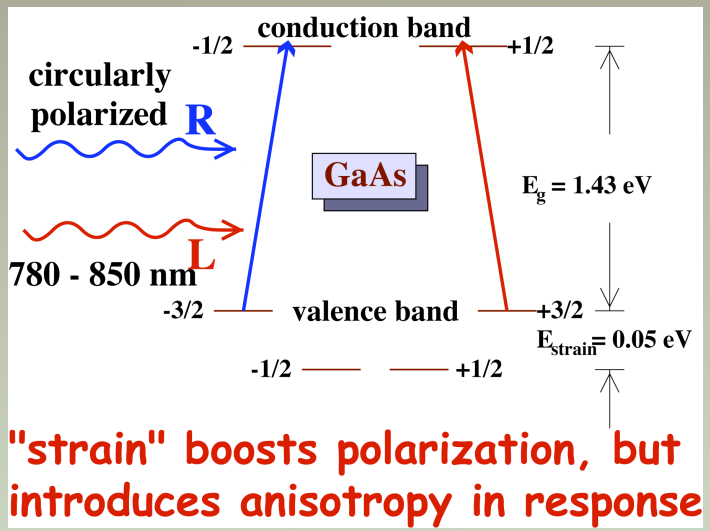
$$\frac{g^2}{2M_\Delta^2} < 0.01\ G_F$$

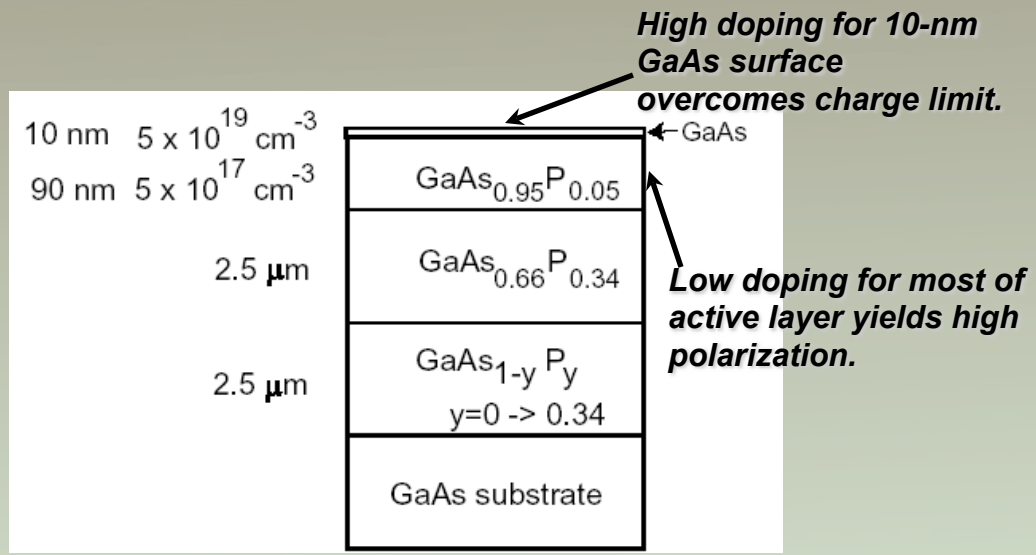
lepton flavor violation

Stanford Linear Accelerator Center

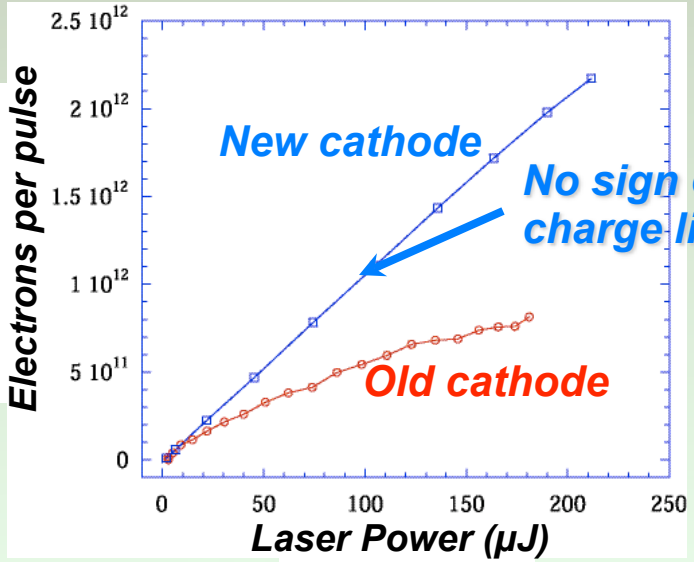


Polarized Beam





Parameter	E158	NLC-500
Charge/Train	6 x 10^{11}	14.3 x 10^{11}
Train Length	270ns	260ns
Bunch spacing	0.3ns	1.4ns
Rep Rate	120Hz	120Hz
Beam Energy	45 GeV	250 GeV
e^- Polarization	80%	80%



Systematic Control

Source Laser Room

IA Feedback Loop

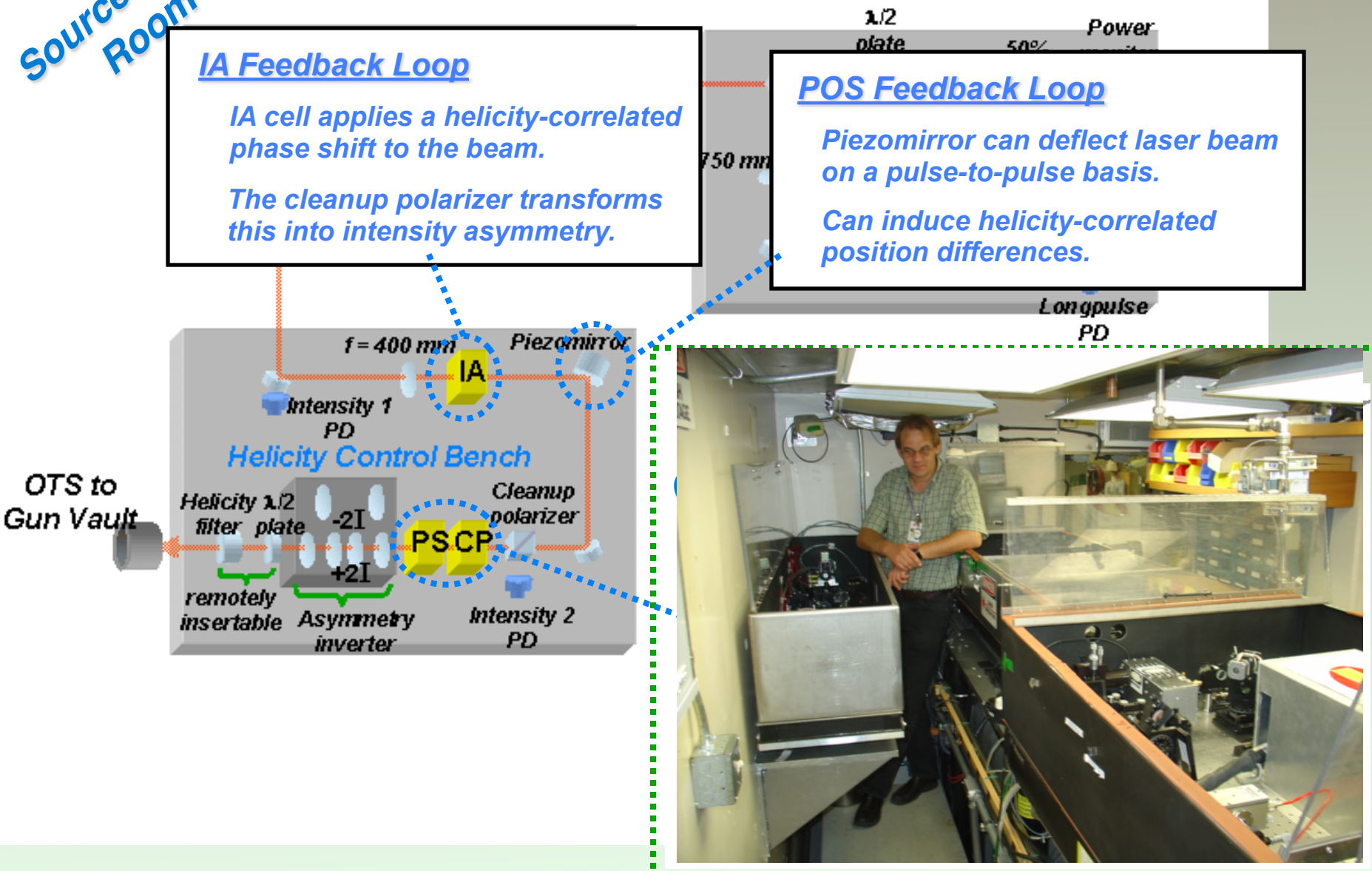
IA cell applies a helicity-correlated phase shift to the beam.

The cleanup polarizer transforms this into intensity asymmetry.

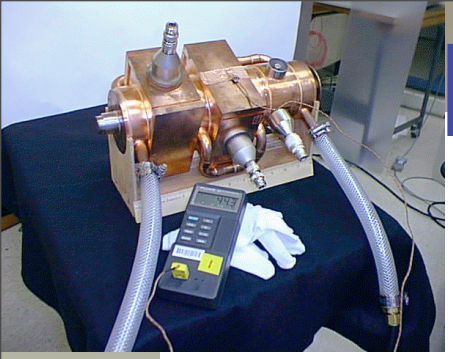
POS Feedback Loop

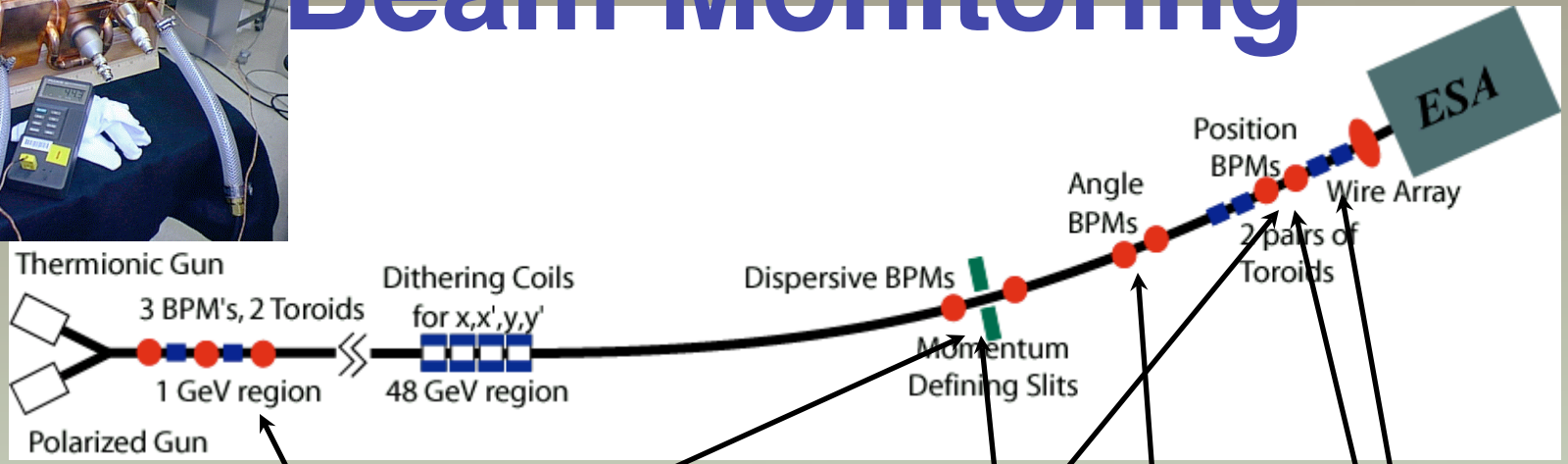
Piezomirror can deflect laser beam on a pulse-to-pulse basis.

Can induce helicity-correlated position differences.



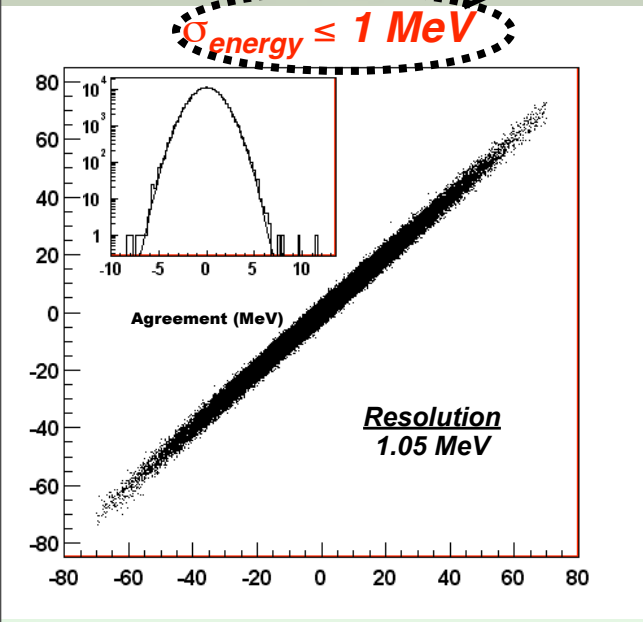
Beam Monitoring



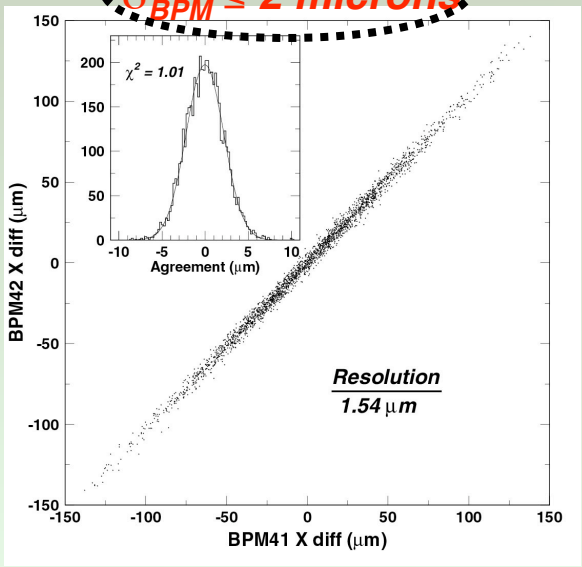


Event by event monitoring at 1 GeV and 45 GeV

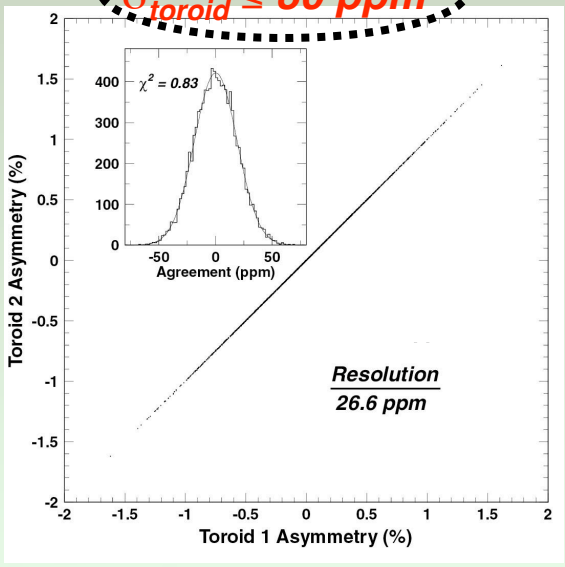
$\sigma_{energy} \leq 1$ MeV



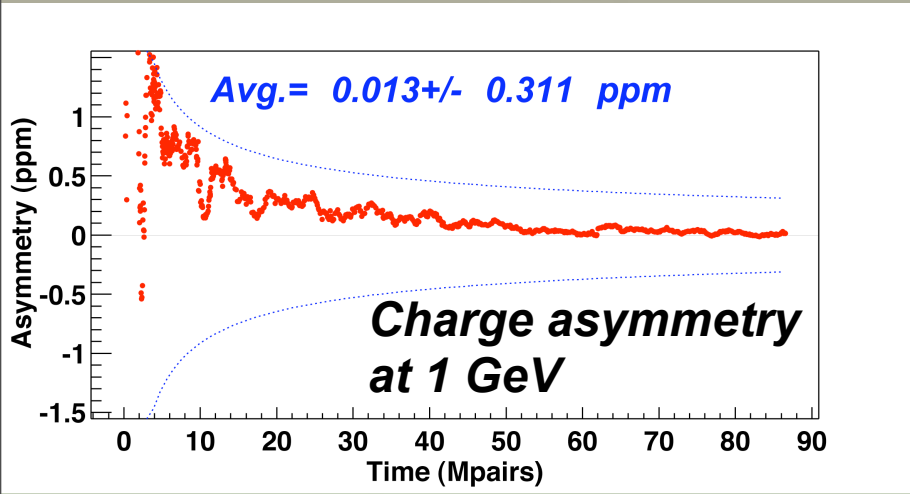
$\sigma_{BPM} \leq 2$ microns

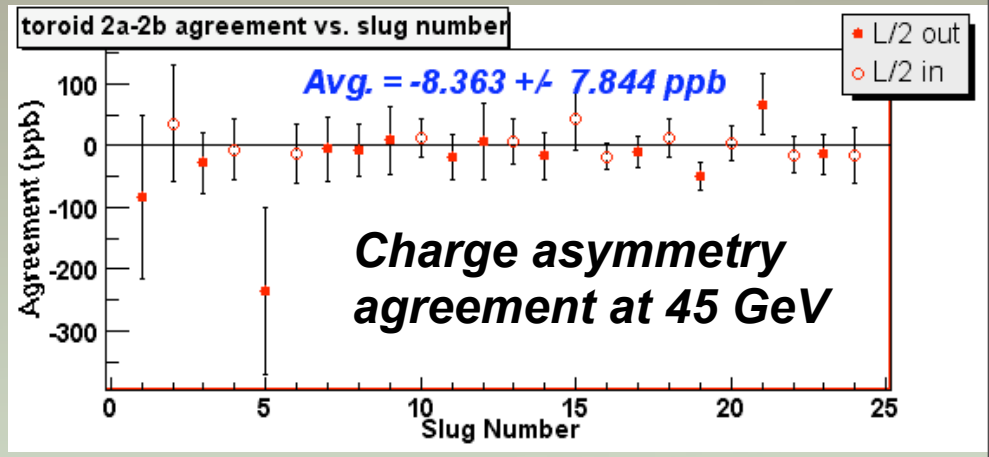


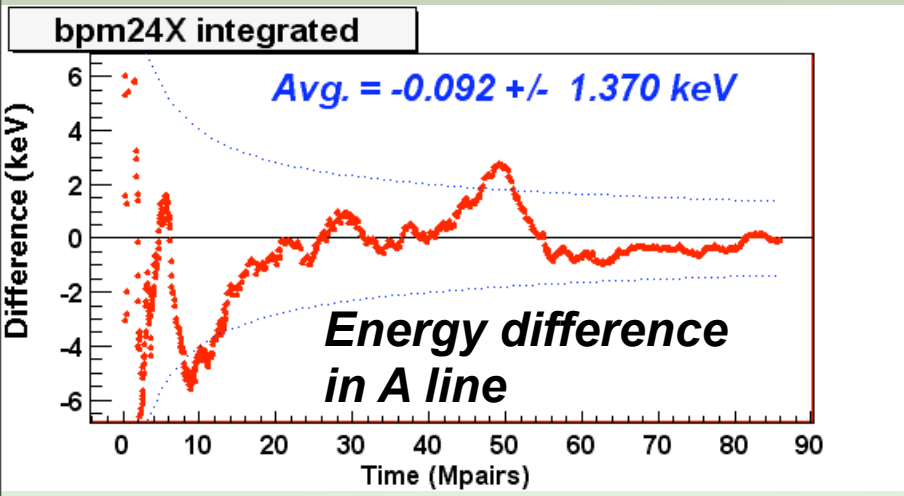
$\sigma_{toroid} \leq 30$ ppm

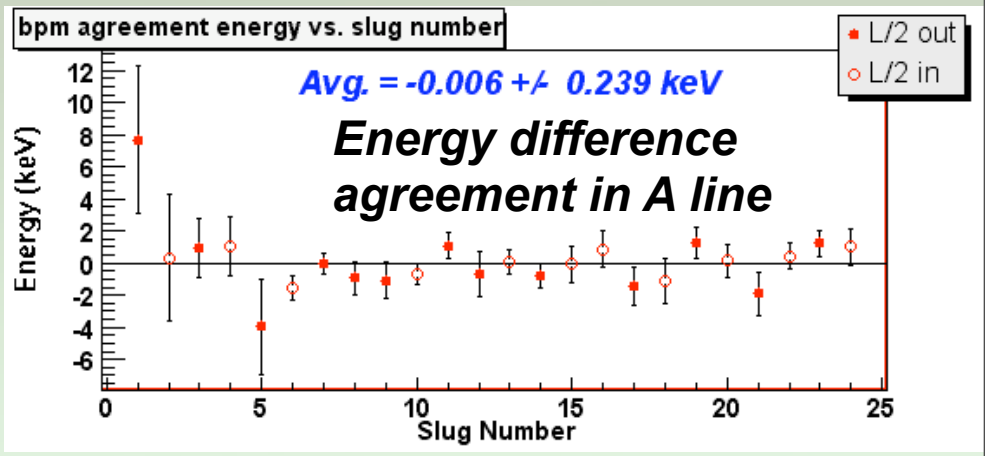


Beam Asymmetries





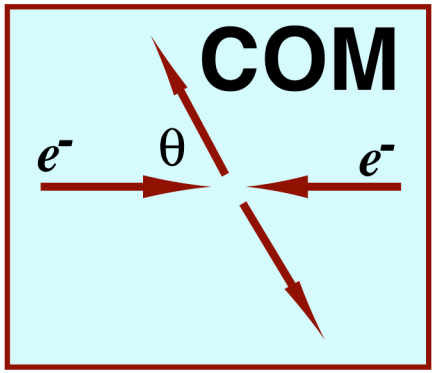


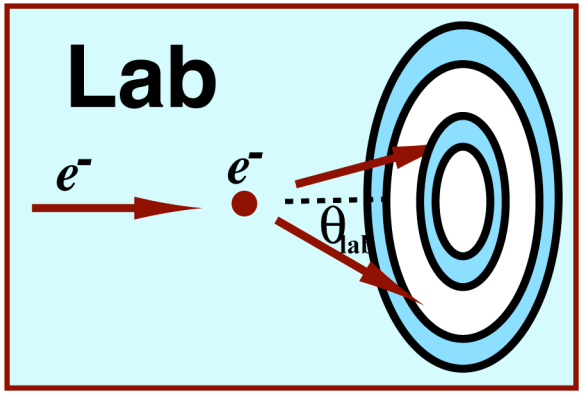


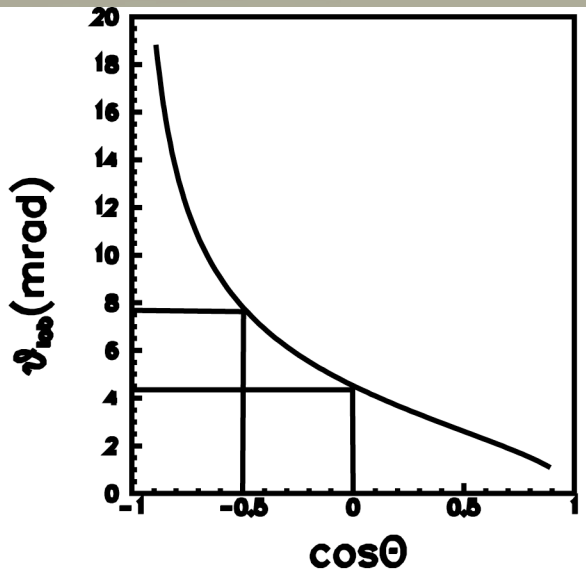
Position differences < 20 nm

Position agreement ~ 1 nm

Kinematics

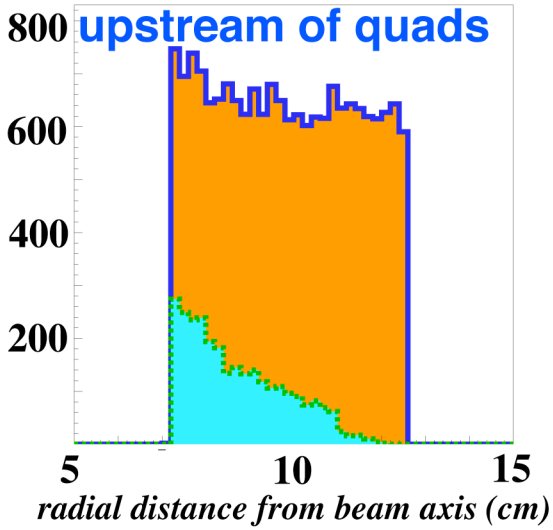


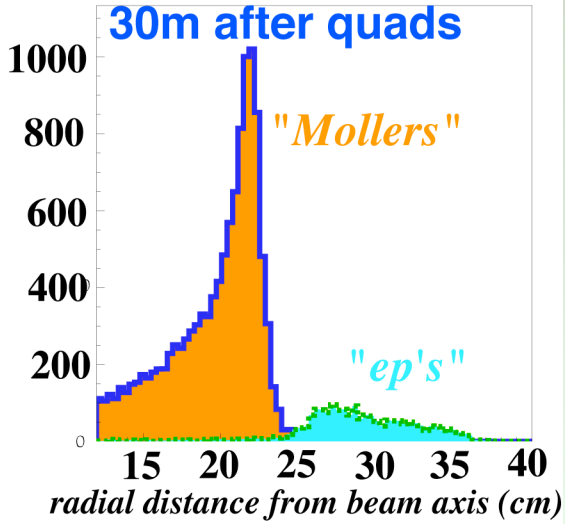




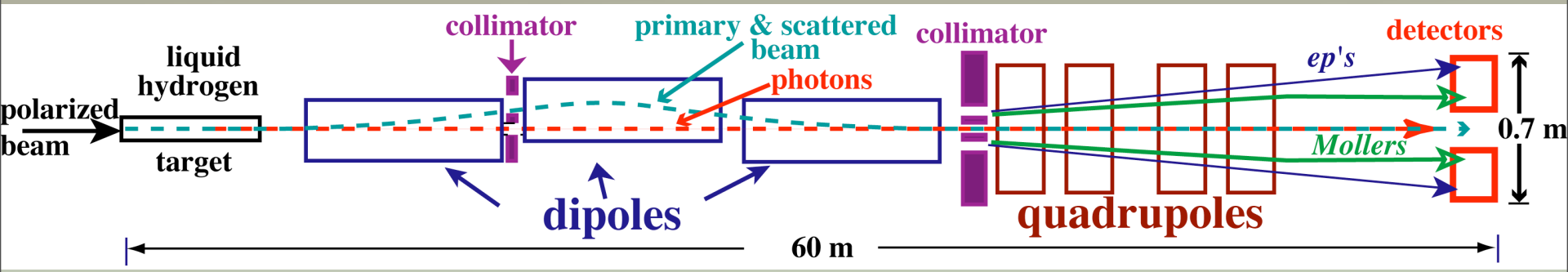
Quadrupole Quadruplet

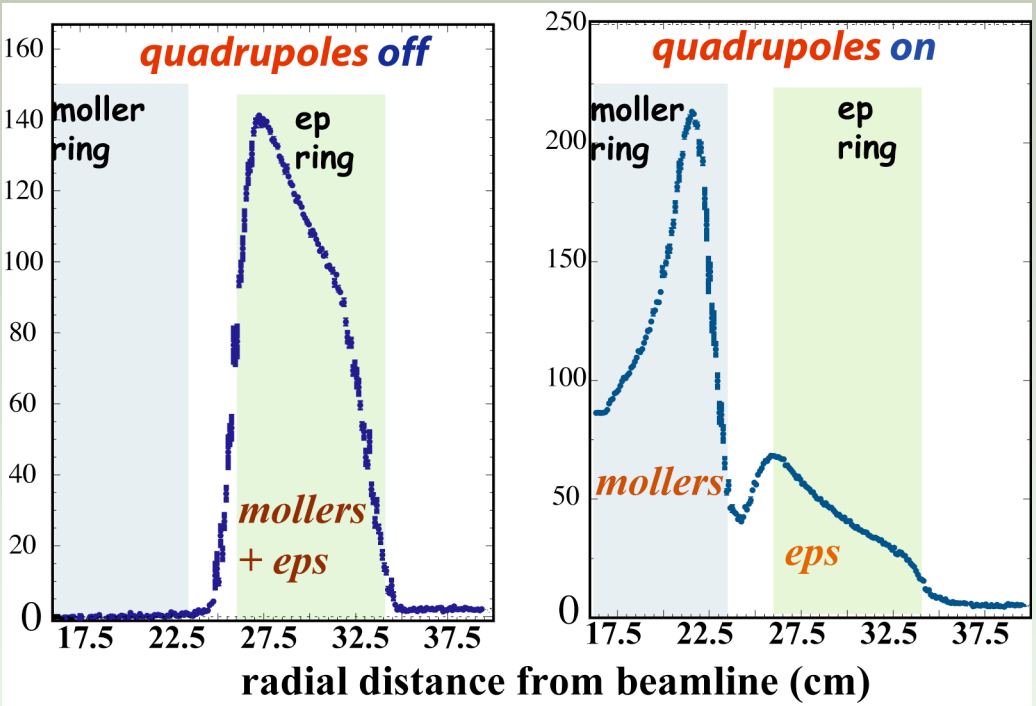
- *primary & scattered electrons enclosed in quadrupoles*
- *Mollers (e-e) focused, Motts (e-p) defocused*
- *full range of azimuth*





Quadupoles and Dipoles



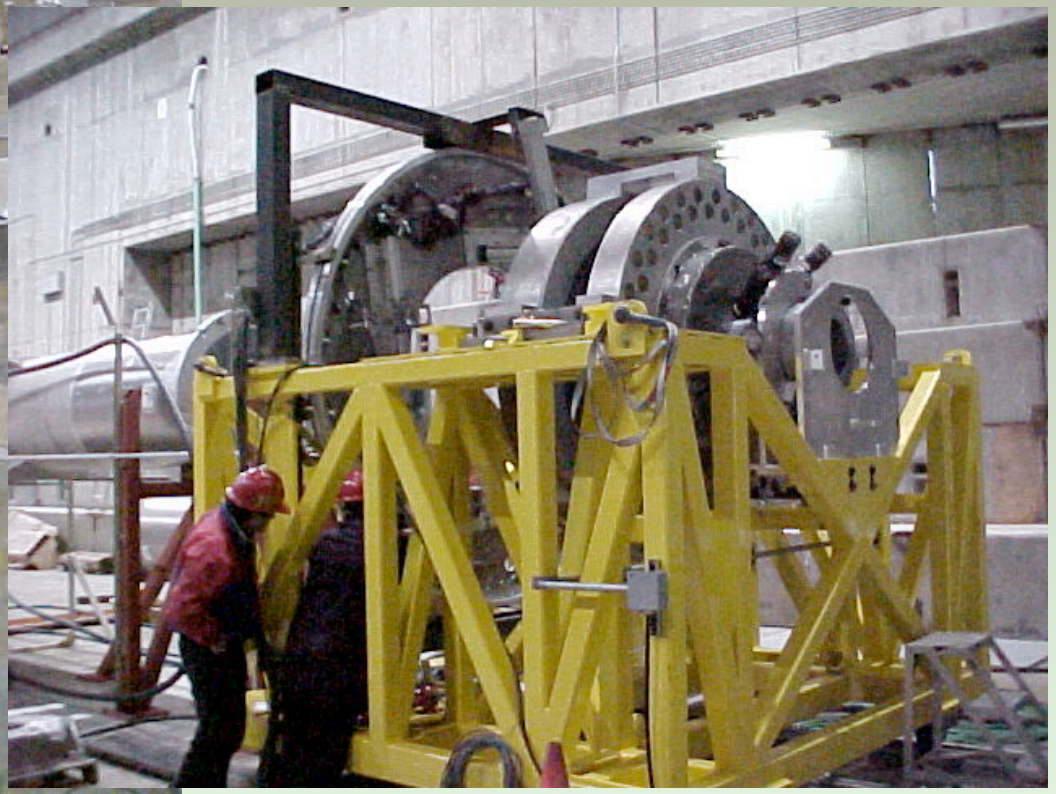


Major Breakthrough:

7 magnetic elements from historic 8 and 20 GeV spectrometer elements

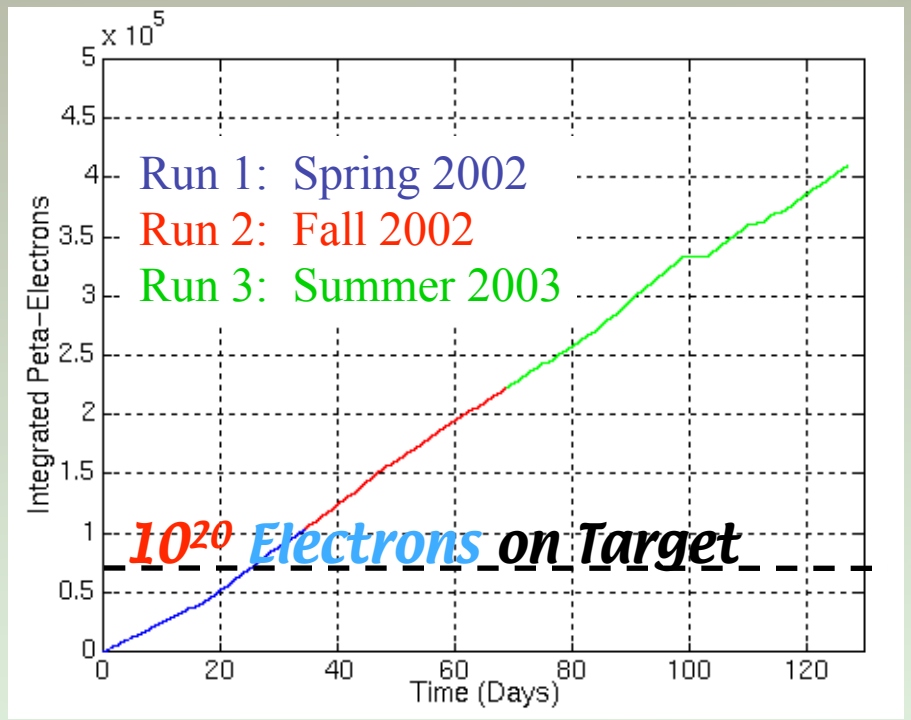
E158 Spectrometer

Downstream Configuration



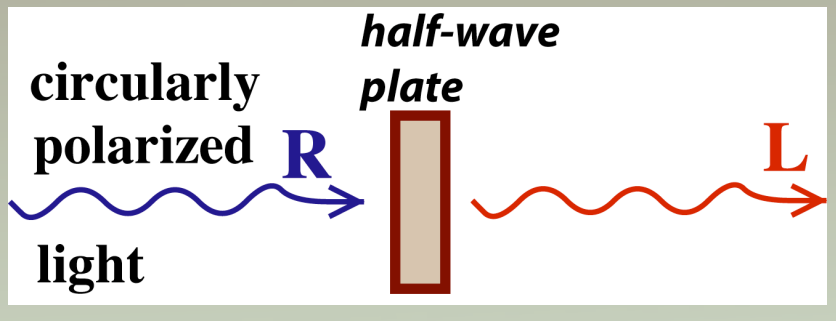
Physics Runs

Run 1: Apr 23 12:00 - May 28 00:00, 2002
Run 2: Oct 10 08:00 - Nov 13 16:00, 2002
Run 3: July 10 08:00 - Sep 10 08:00, 2003



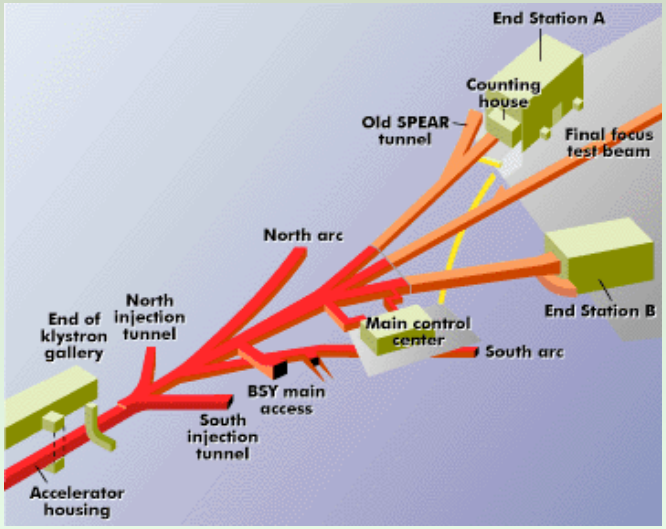
Data divided into 75 "slugs":
- Wave plate flipped ~ few hours
- Beam energy changed ~ few days

A_{PV} Sign Flips

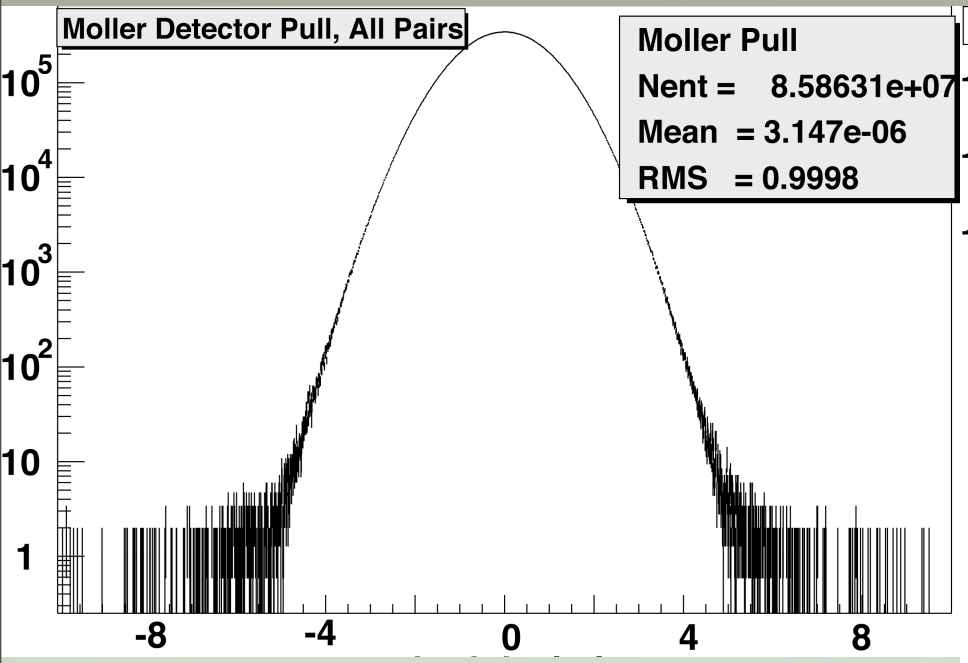


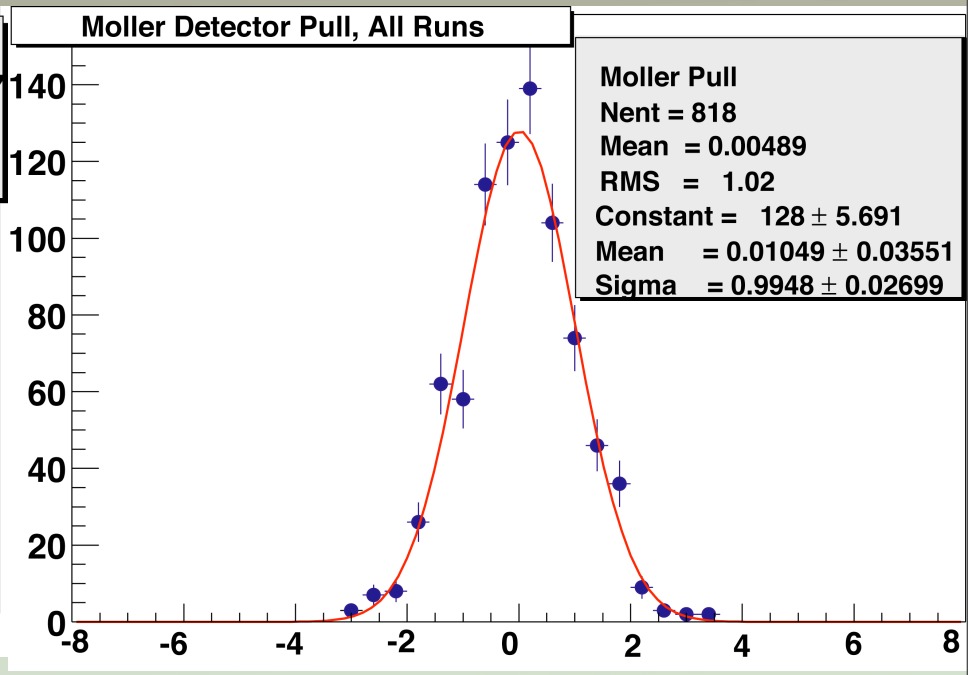
g-2 spin precession

45 GeV: 14.0 revs
48 GeV: 14.5 revs



Raw Asymmetry





$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

$\sigma_i \approx$ *200 ppm*

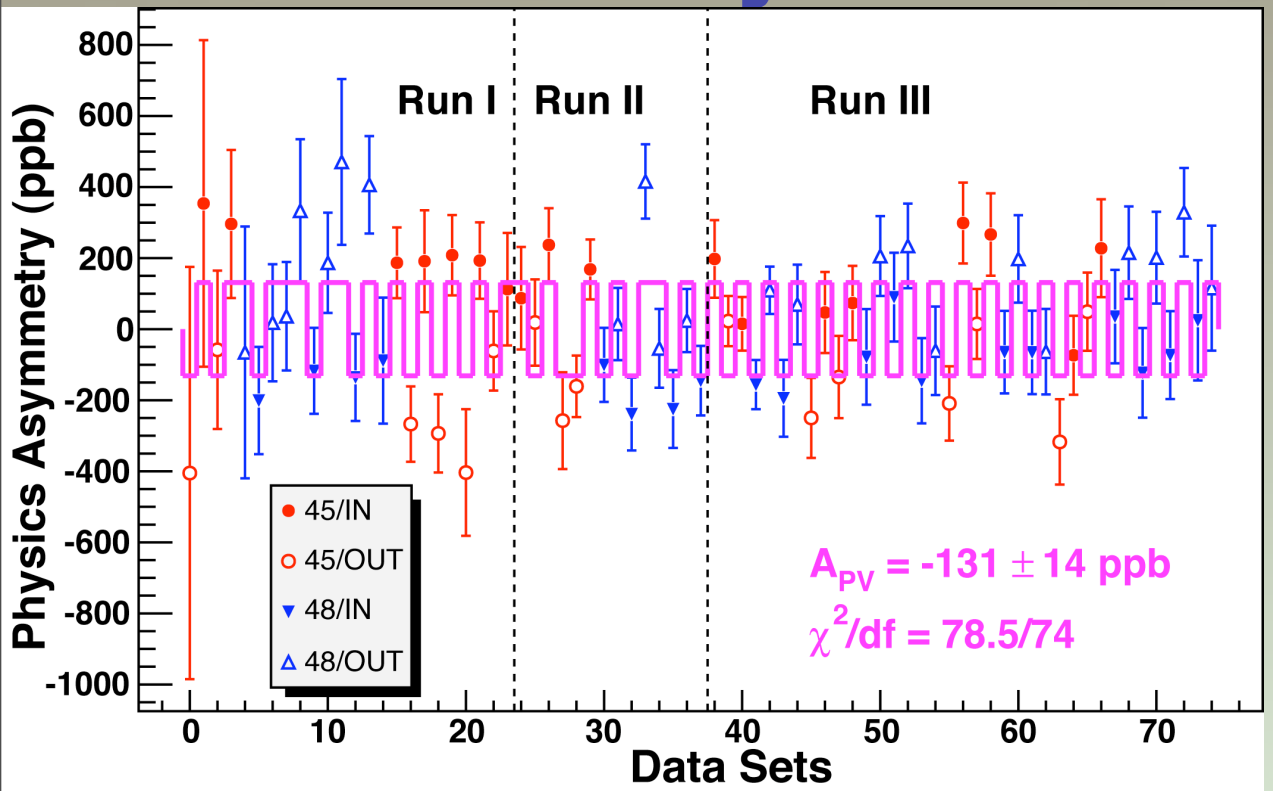
N = 85 Million

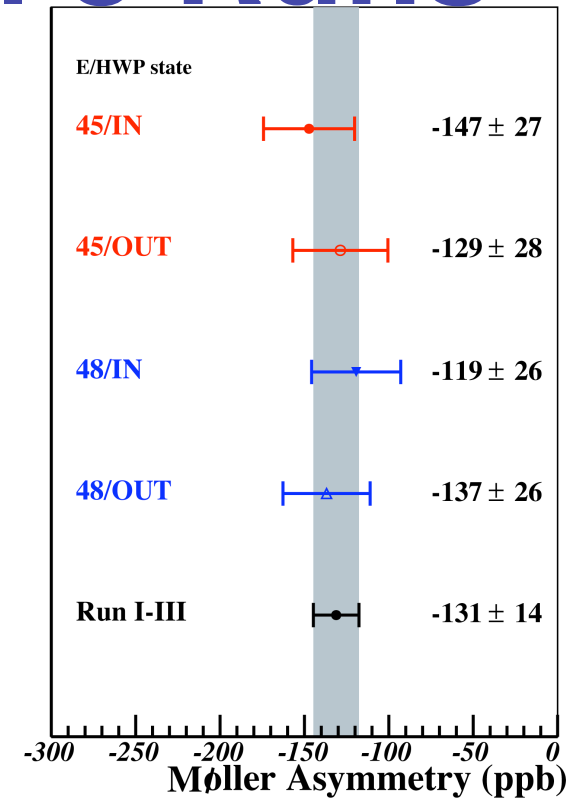
$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

$\sigma_i \approx$ *600 ppb*

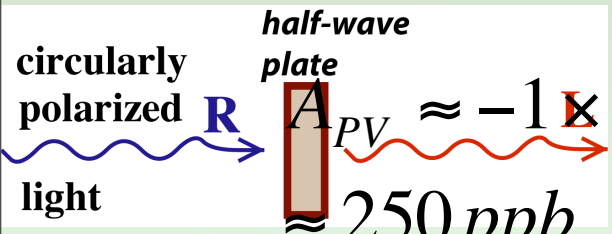
N = 818

Final Analysis of All 3 Runs





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



$$A_{PV} \approx -1 \times 10^{7} \times E_{beam} \times P_{beam} \times (1 - 4\sin^2\vartheta_W)$$

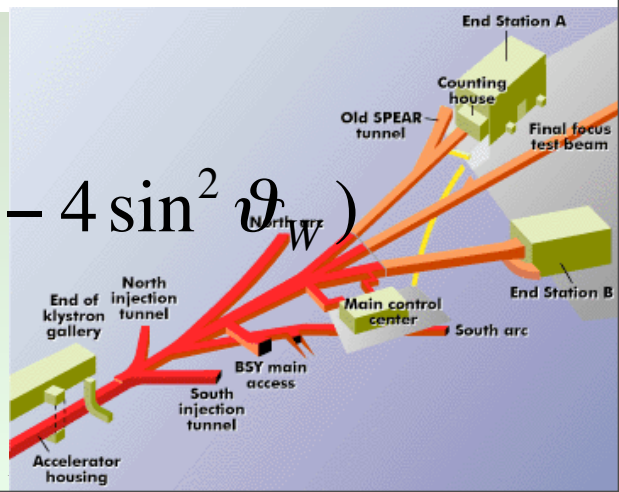
$$\approx 250\,ppb$$

g-2 spin precession

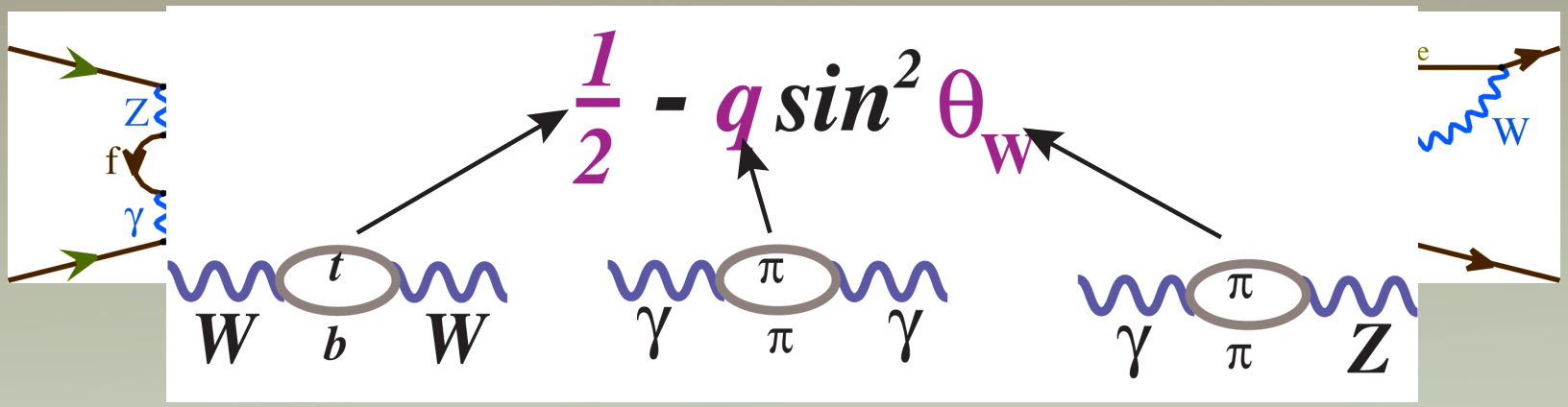
45 GeV: 14.0 revs

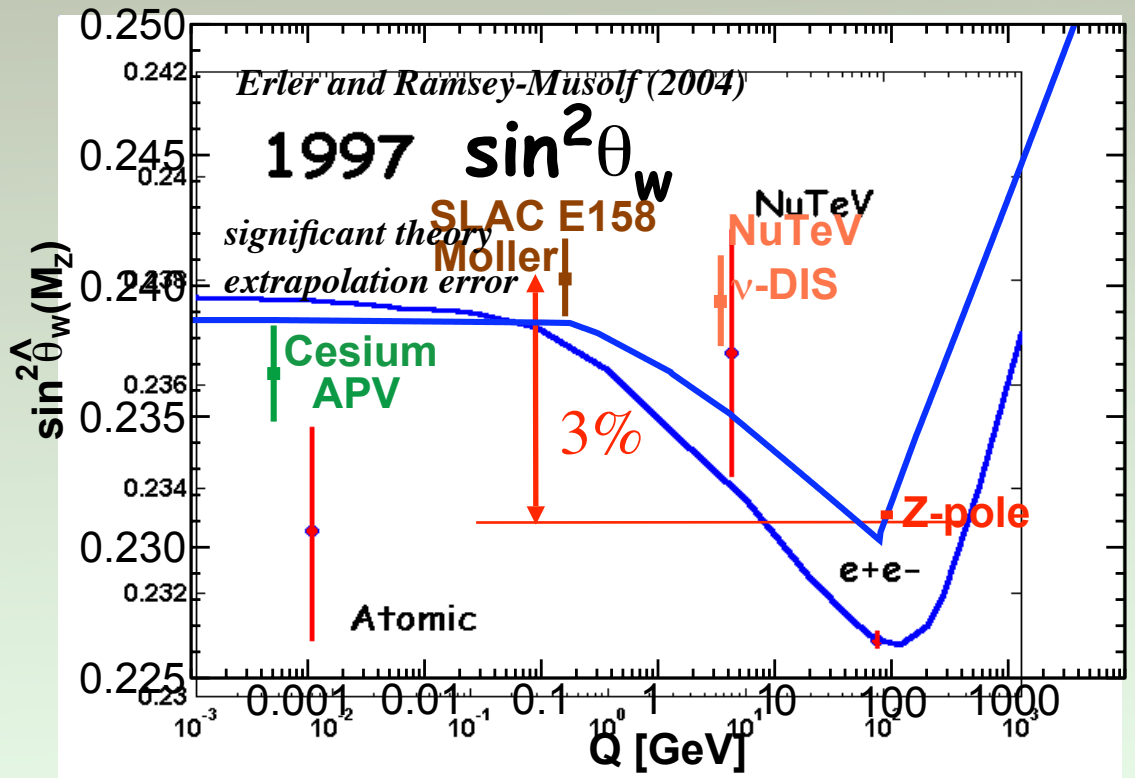
48 GeV: 14.5 revs

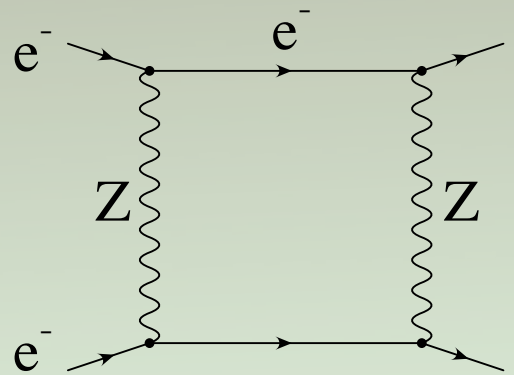
Phys. Rev. Lett. **95** 081601 (2005)



Electroweak Physics







- *Czarnecki and Marciano (2000)*
- *Petriello (2002)*
- *Erler and Ramsey-Musolf (2004)*
- *Sirlin et. al. (2004)*
- *Zykonov (2004)*

Fixed Target EW Physics in 2009

LHC might find new phenomena, but deciphering the underlying dynamics will require other indirect signatures

- ***Neutrons***
  - Lifetime, P- & T-Violating Asymmetries
    - *LANSCE, NIST, SNS*
- ***Parity-Violating Electron Scattering***
  - Weak mixing angle, Strange quark structure, Ground State Neutron Distribution
    - *MIT-Bates, SLAC, Mainz, Jefferson Lab*
- ***Muons***
  - Michel parameters, lifetime, muon capture, g-2 anomaly, charged lepton flavor violation
    - *PSI, TRIUMF, BNL, FNAL*

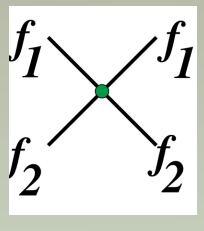
A strong case made at the Nuclear Physics Long Range Planning Process

Comprehensive Search for New Neutral Current Interactions

Important component of indirect signatures of "new physics"

Consider $f_1\bar{f}_1 \rightarrow f_2\bar{f}_2$ or $f_1 f_2 \rightarrow f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2} \eta_{ij} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma^\mu f_{2j}$$



Eichten, Lane and Peskin, PRL50 (1983)

Λ's for all $f_1 f_2$ combinations and L,R combinations

Many new physics models give rise to non-zero Λ's at the TeV scale: Heavy Z's, compositeness, extra dimensions…

One goal of neutral current measurements at low energy AND colliders: Access $\Lambda > 10$ TeV for as many $f_1 f_2$ and L,R combinations as possible

LEPII, Tevatron access scales Λ's ~ 10 TeV

e.g. Tevatron dilepton spectra, fermion pair production at LEPII

- L,R combinations accessed are parity-conserving

LEPI, SLC, LEPII & HERA accessed some parity-violating combinations but precision dominated by Z resonance measurements

Møller Scattering at 11 GeV

Parity-Violating Møller Scattering:
Luminosity and Stability at Jlab upgrade makes feasible a factor of 5 improvement over E158

$\sin^2\theta_W$ to ± 0.00025
Λ_{ee} ~ 25 TeV reach

Best new measurement until Linear Collider or Neutrino Factory

Proposal submitted to PAC34

$$A_{PV} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e$$

E_{beam} = 11 GeV 75 μA 80% polarized $\xrightarrow[(\sim 2\ yrs)]{\sim 38\ weeks}$ $\delta(A_{PV})$ = 0.73 ppb

A_{PV} = 35.6 ppb ⇒ $\delta(Q^e_W)$ = ± 2.1 (stat.) ± 1.0 (syst.) %

$\delta(\sin^2\theta_W)$ = ± 0.00026 (stat.) ± 0.00012 (syst.) ⇒ ~ 0.1%

⇒ not just "another measurement" of $\sin^2\theta_W$; 0.0003 passes a threshold

Compelling opportunity with high luminosity, polarized 11 GeV beam:

- Comparable to the two best measurements at colliders
- Unmatched by any other project in the foreseeable future
- At this level, one-loop effects from "heavy" physics

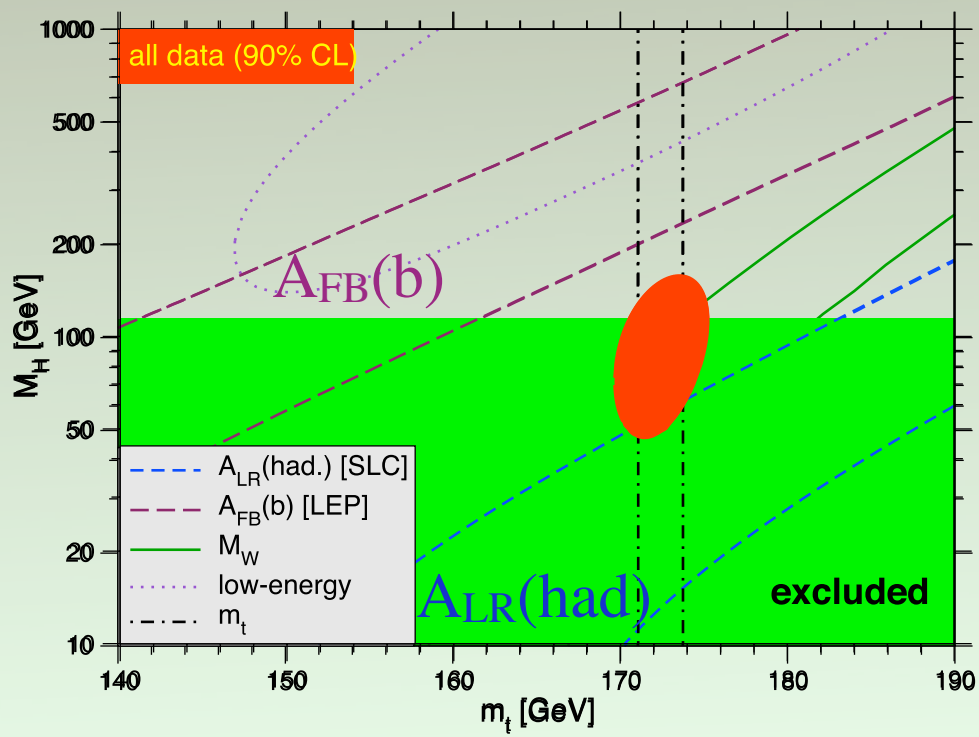
EW Physics at One-Loop

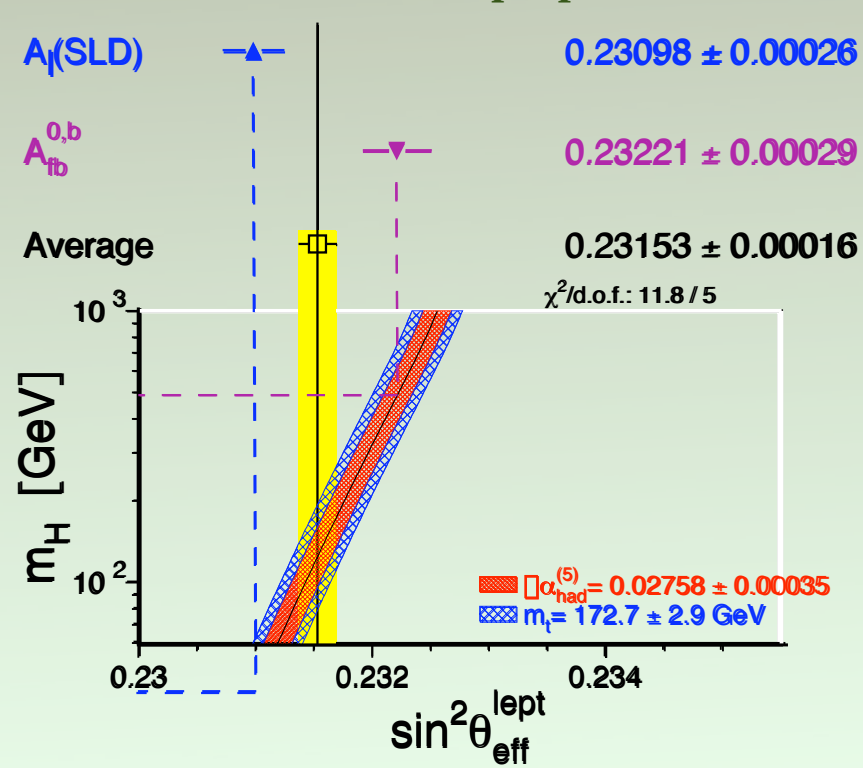
Three fundamental inputs needed: α_{em}, G_F and M_Z

Other experimental observables predicted at 0.1% level: sensitive to heavy particles via higher order quantum corrections

(additional input from fermion masses, mixing and α_{strong})

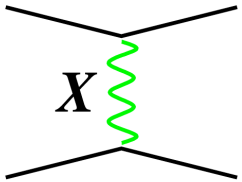
4th and 5th best measured parameters: $\sin^2\theta_W$ and M_W



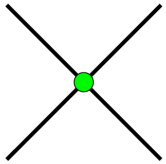


Off the Z Resonance

consider



$$A_X \propto \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2}$$



Contact interaction

$Q^2 \sim M_Z^2$ **on resonance:** A_Z *imaginary* $\longrightarrow A_Z^2 \left[1 + \frac{A_X^2}{A_Z^2} \right]$

no interference!

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \xrightarrow{A_{PV}} \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

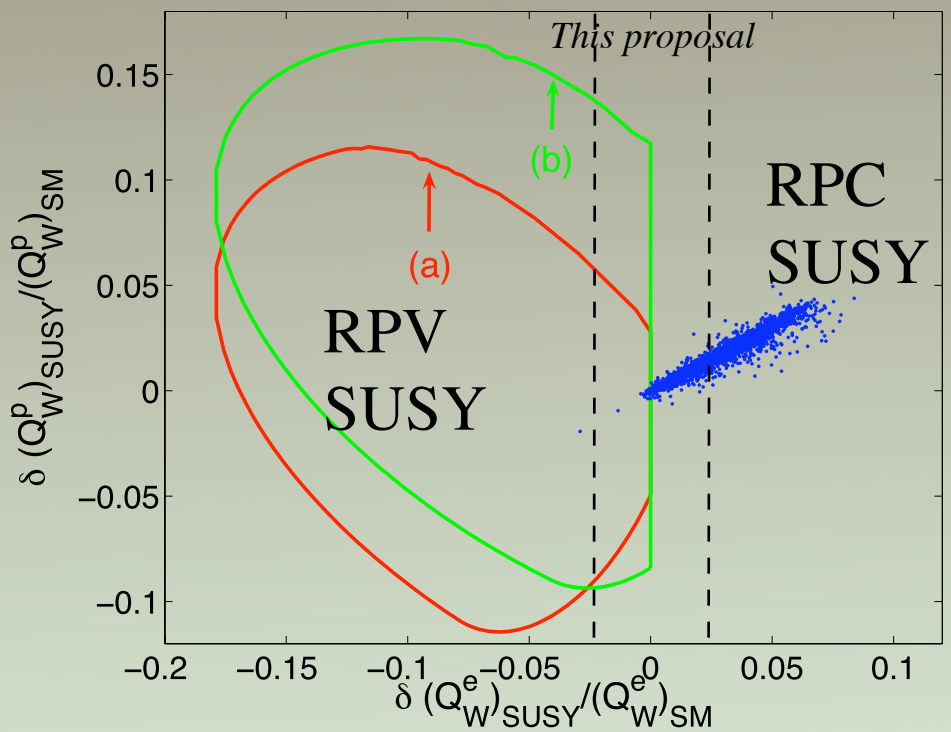
Best current limits on 4-electron contact interactions: LEPII at 200 GeV

(Average of all 4 LEP experiments)

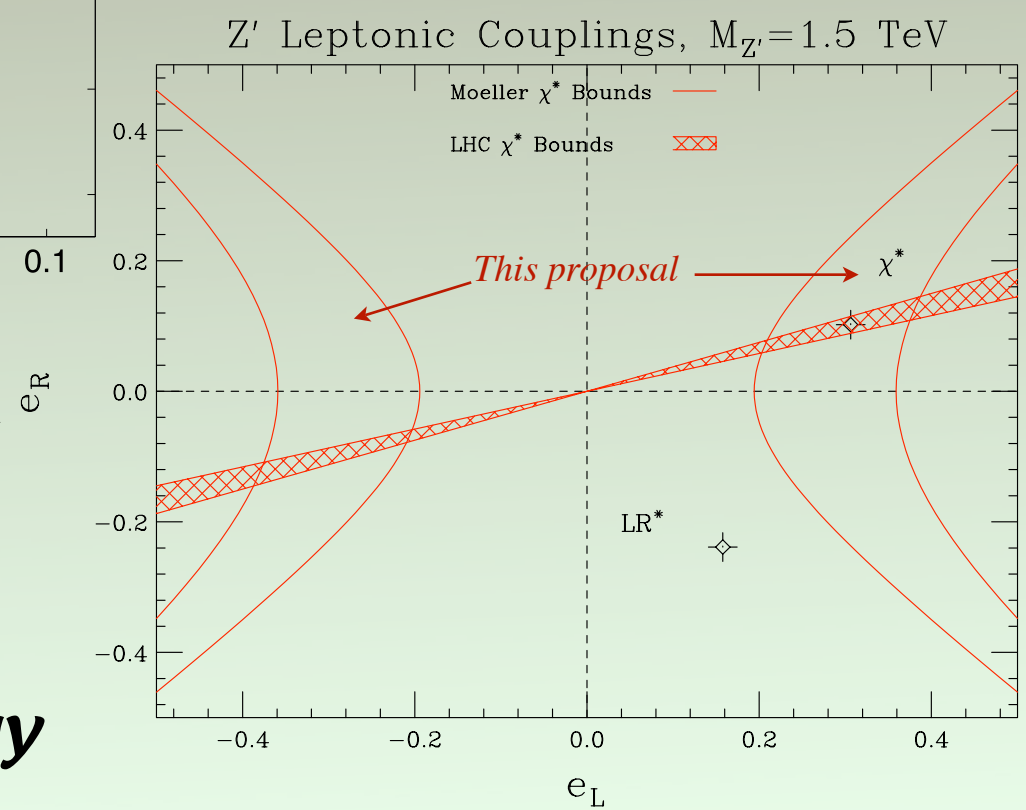
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 + g_{LL}^2|}} = 4.4 \text{ TeV} \quad \text{OR} \quad \frac{\Lambda}{g_{RL}} = 5.2 \text{ TeV}$$

insensitive to $|g_{RR}^2 - g_{LL}^2|$

Two Examples



- *LHC Z' reach ~ 5 TeV*
- *With high luminosity, 1-2 TeV Z' properties can be extracted*
- *A_{PV} can help separate left- and right-handed couplings*



- *MSSM sensitivity if light super-partners, large tanβ*
- *If R-parity violated, no SUSY dark matter candidate*

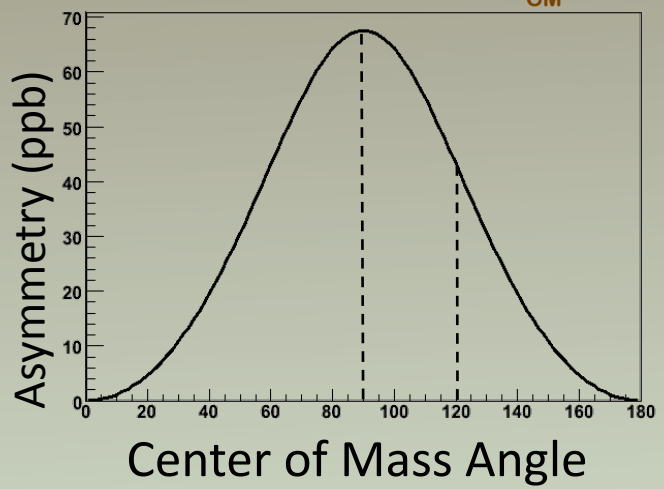
Important for cosmology

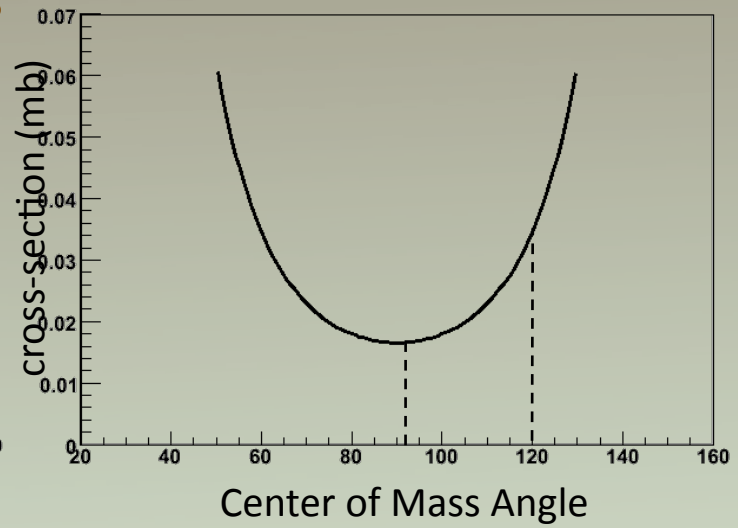
New Challenges

- *~ 150 GHz scattered electron rate*
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 10^{-5}*
    - *Pulse-to-pulse beam jitter ~ 10s of microns at 1 kHz*
    - *Pulse-to-pulse beam monitoring resolution ~ few micron at 1 kHz*
- *1 nm control of beam centroid on target*
  - Modest improvement on control of polarized source laser transport elements
  - Improved methods of "slow helicity reversal"
- *> 10 gm/cm^2 target needed to achieve desired luminosity*
  - 1.5 meter Liquid Hydrogen target: ~ 5 kW @ 85 μA
- *Full Azimuthal acceptance with θ_{lab} ~ 5 mrad*
  - novel two-toroid spectrometer
  - radiation hard integrating detectors
- *Robust and Redundant 0.4% beam polarimetry*
  - Plan to pursue both Compton and Atomic Hydrogen techniques

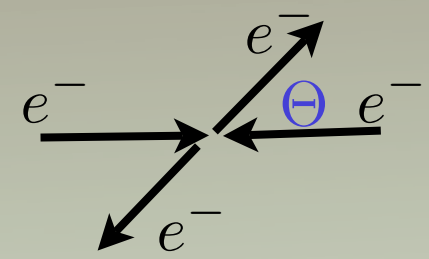
100% Acceptance with Toroids

Highest figure of merit at $\theta_{CM} = 90^o$



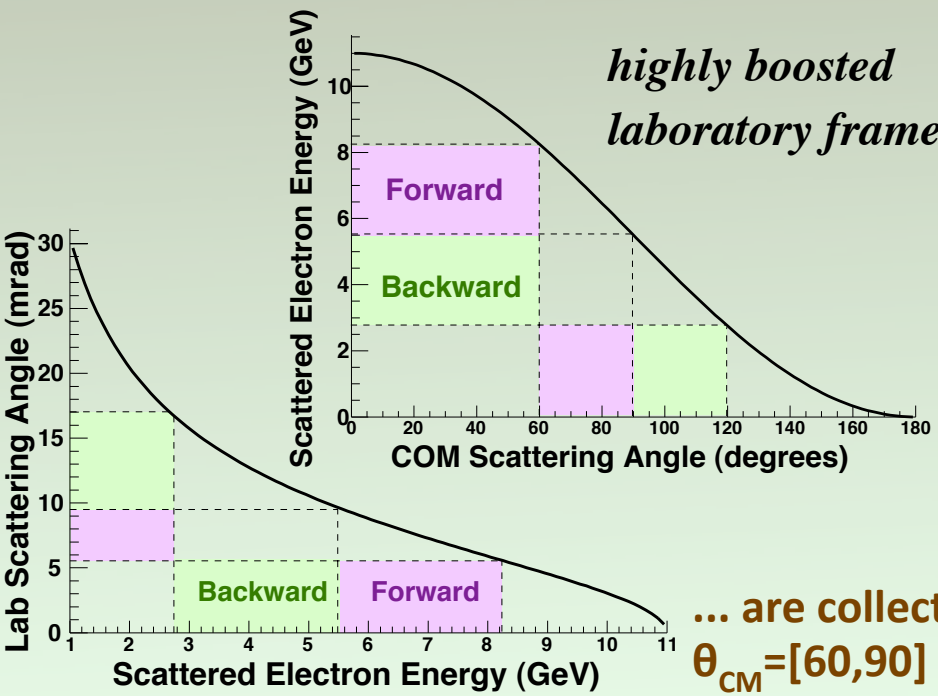


$E_{COM} = 53$ MeV

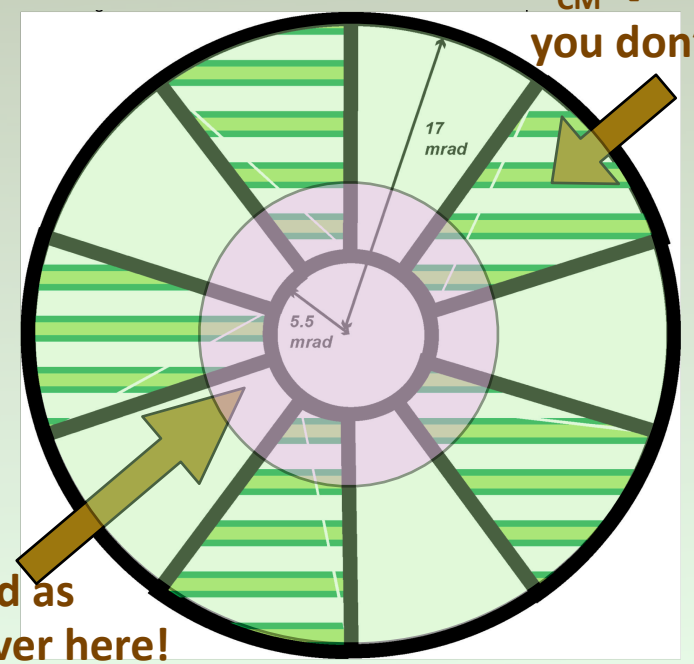


identical particles!

All of those rays of θ_{CM}=[90,120] that you don't get here...

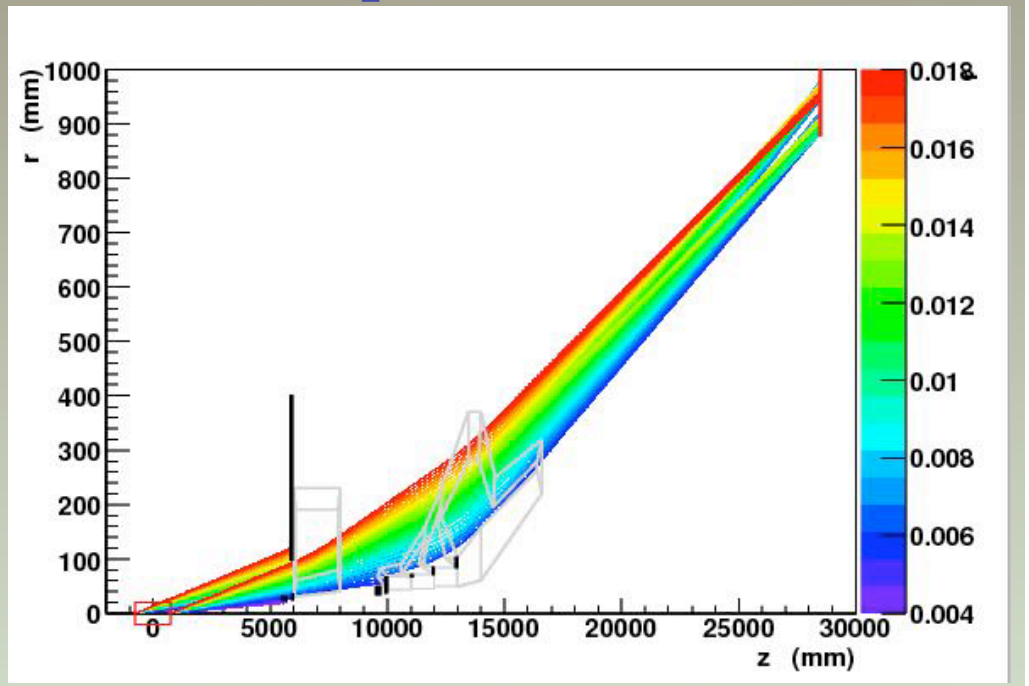


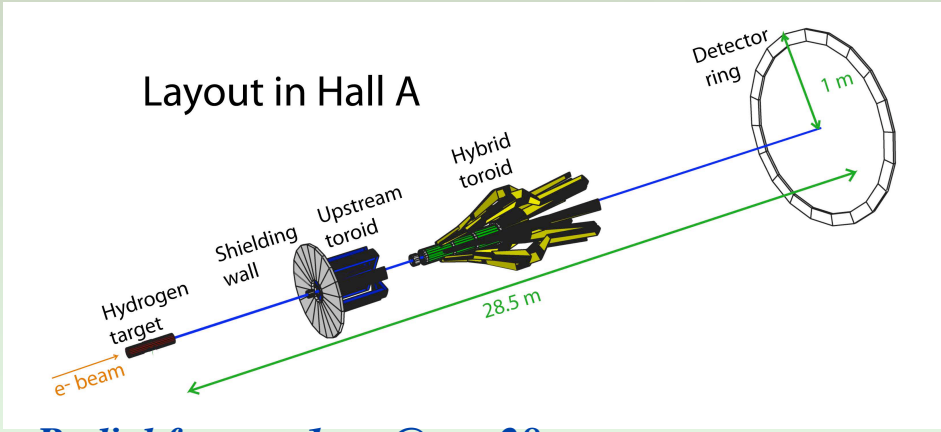
highly boosted laboratory frame

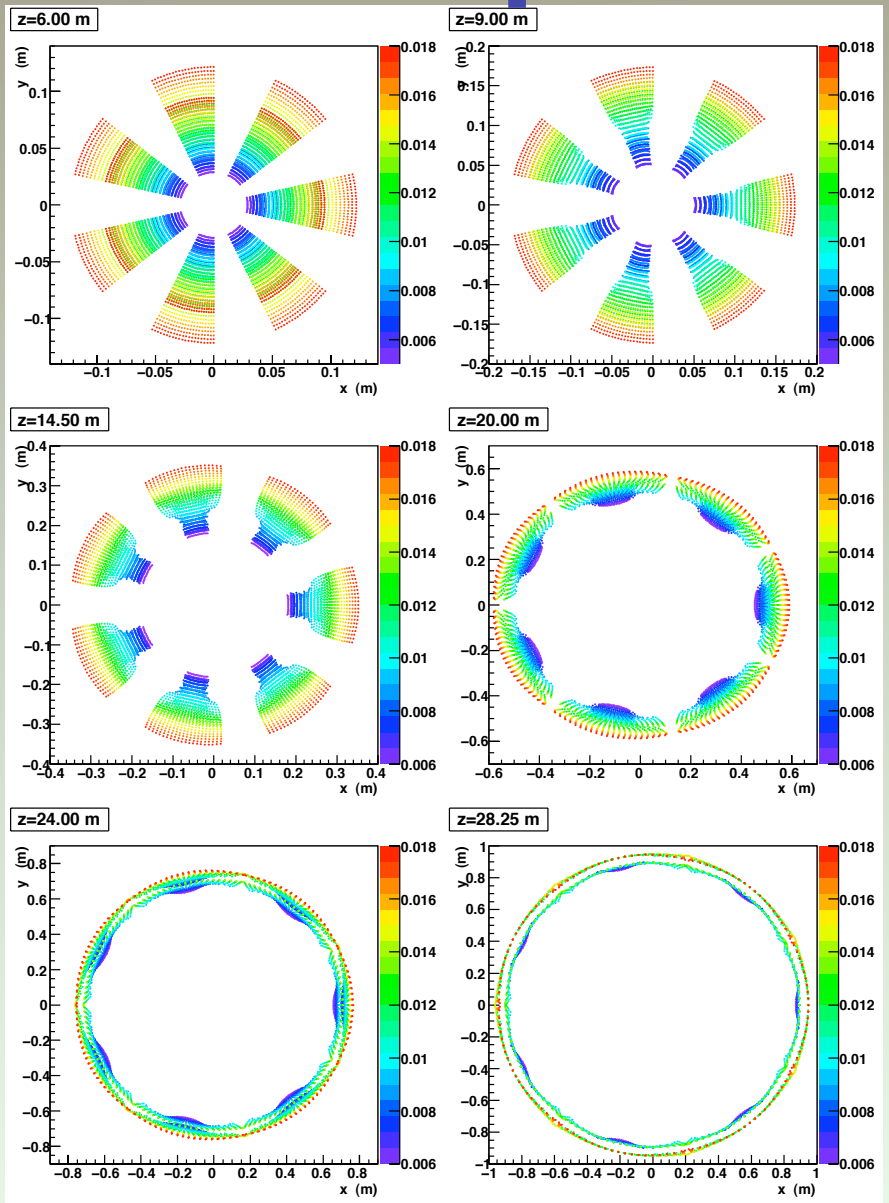


... are collected as θ_{CM}=[60,90] over here!

Spectrometer Concept

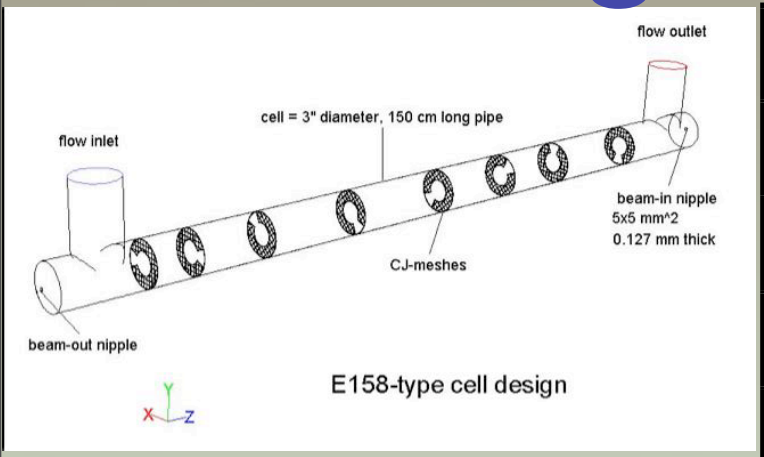




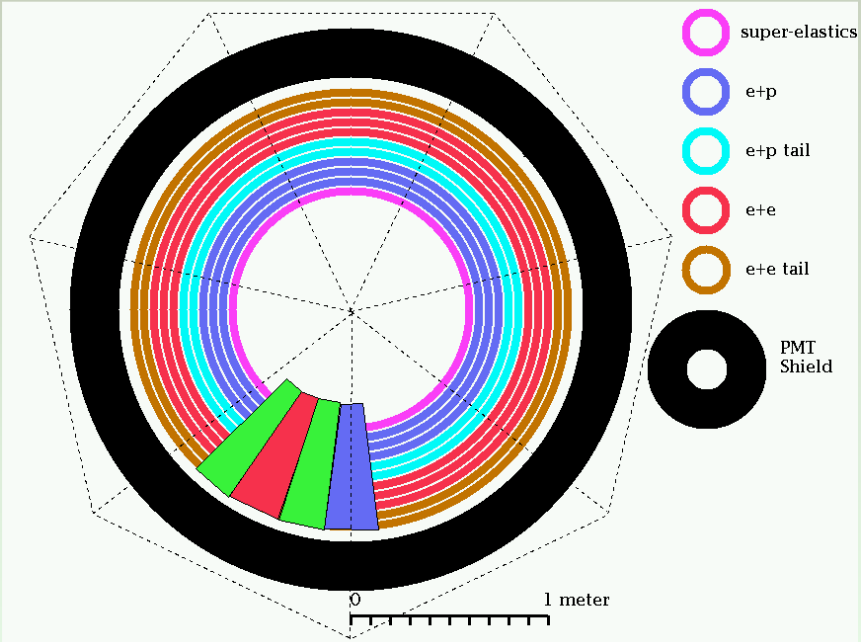


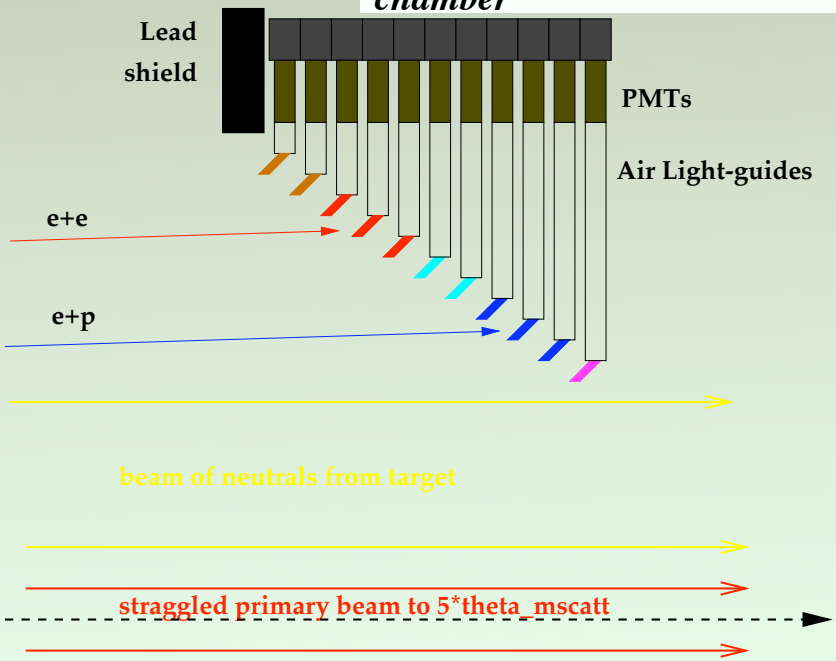
- ***Radial focus ~ 1 m, @ z ~ 28 m***
- ***Defocusing results in population of full azimuth***

Target & Detectors



parameter	value
length	150 cm
thickness	10.7 gm/cm^2
X_0	17.5%
p,T	35 psia, 20K
power	5000 W

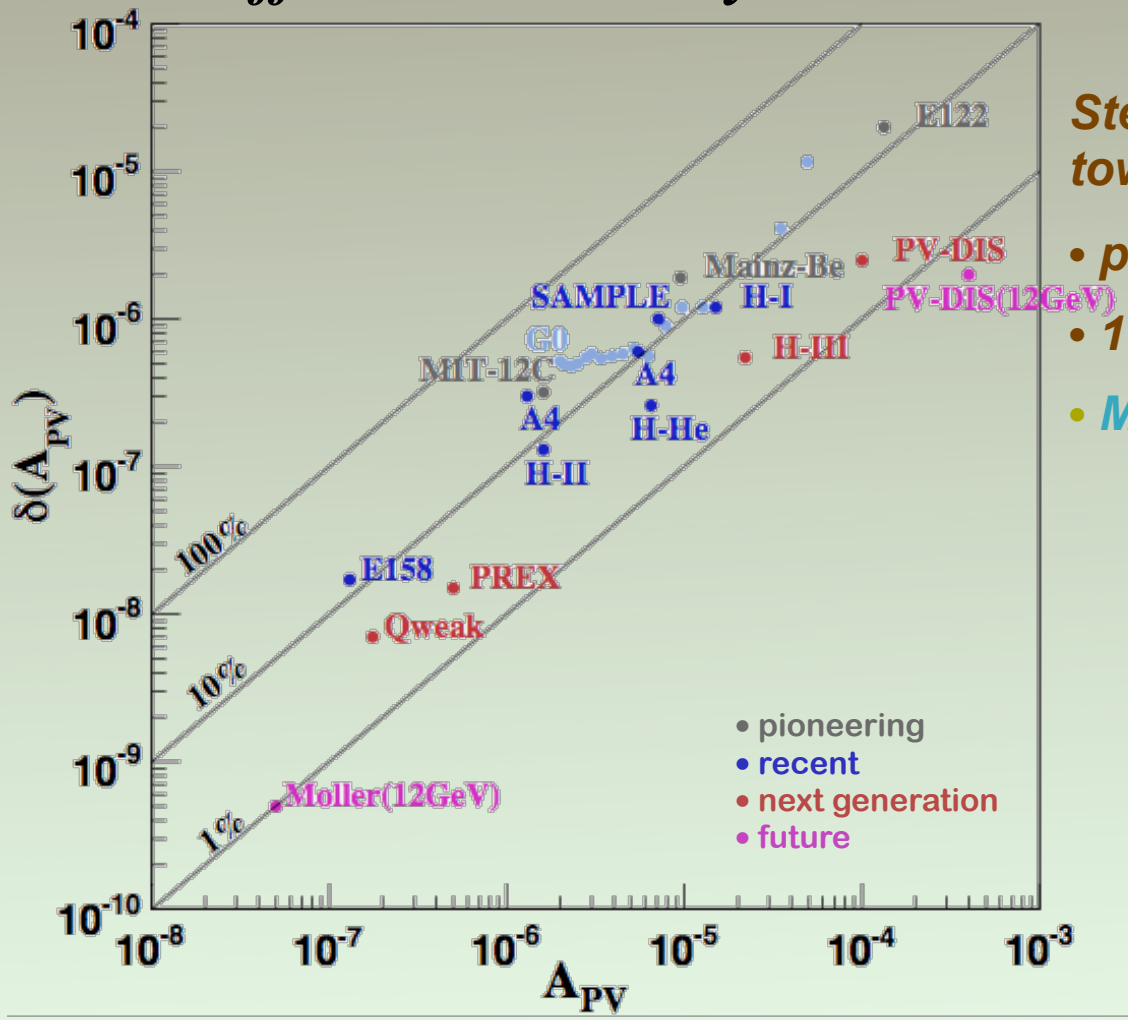




Technical Improvements over 3 Decades

Parity-violating electron scattering has become a precision tool

Jefferson Laboratory has now become the central player



Steady progress in technology towards:

- *part per billion systematic control*
- *1% systematic control*
- *Major developments in*
  - *photocathodes (I & P)*
  - *polarimetry*
  - *high power cryotargets*
  - *nanometer beam stability*
  - *precision beam diagnostics*
  - *low noise electronics*
  - *radiation hard detectors*

Outlook for Proposal

- ***Strong Collaboration formed***
  - Synergy with PVDIS proposal
  - Expertise from PREX, Qweak and E158
  - 4th generation JLab parity experiment
  - Major interest and commitment to development of apparatus given funding
  - Will actively seek more foreign participation
  - If approved, will solicit new funding from DoE, NSF and foreign sources

An Ultra-precise Measurement of the Weak Mixing Angle using Møller Scattering

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Summary

- *Møller Scattering has played a central role in our understanding of electromagnetic and weak interactions*
- *PAC 34 proposal is compelling opportunity to carry this physics forward, with high visibility and large potential payoff*
  - The weak mixing angle is a fundamental parameter of EW physics
  - HEP has tried to come up with a cost-effective project for years
    - *expensive ideas reach perhaps 0.2% (reactor or accelerator ν's, LHC Z production...)*
    - *sub-0.1% requires a new machine (e.g. Z- or ν-factory, linear collider....)*
  - physics impact on nuclear physics, particle physics and cosmology
- *NSAC Long Range Plan strongly endorsed the physics*
  - part of fundamental symmetries initiative to tune of 25M$
- *11 GeV JLab beam is a unique instrument that makes this feasible*
- *Perhaps Jefferson Lab is launching the most important chapter in the final decade of the 100 year history of Møller scattering!*