Electroweak Physics

Lecture III:

Electroweak Physics at Low Q^2: Weak Neutral Current Interactions

Review

- The electroweak theory has been tested to extraordinary precision
- Typical scale is 0.1%
- No significant deviations, but some tantalizing hints
- The Higgs boson is expected to be light
- We have a self-consistent effective quantum field theory of electroweak interactions up to a scale of 100 GeV
- There has been much progress, but many questions remain

Big Questions (EW physics)

- Why 3 generations of particles?
- Why is the weak boson mass ~ 100 GeV?
- What is the origin of mass?
- How did matter dominate over anti-matter?
- Is there a single unifying force?
- Why are neutrinos so light?
- Why is the Top so heavy?
- …….

The High Energy Frontier

- Directly access the 1 TeV scale
- Explore the origin of SU(2) X U(1) symmetry breaking
- Measure the arbitrary parameters as precisely as possible
- Confirm or rule out Supersymmetry

Low Energy EW Physics

- Symmetries & Conservation Laws
  - **Atomic and Nuclear systems offer rare, unique access to EW interactions**
  - **Indirect access to very high energy scales**
  - **Clues to Grand Unified Theories**
  - **High statistics $\rightarrow$ Rare processes**
- Evolution of fundamental coupling constants
  - **Test theory at quantum loop level**
  - **Indirect access to high energy particles**

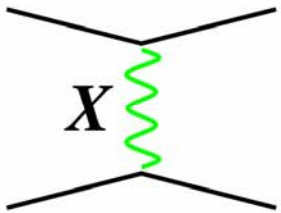
Weak Neutral Current Interactions

- Many contrasts to W interactions:
  - **Flavor conserving**
  - **Mixing with electromagnetism**
  - **Better control in the laboratory**
- Most new theories have many heavy neutral bosons
- Precision knowledge of Z couplings to all fermions to interpret collider data

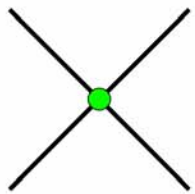
WNC Interactions at Low Q^2

Q^2 << scale of EW symmetry breaking

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!

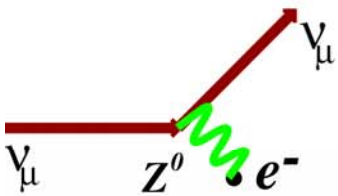
Logical to push to higher energies, away from the Z resonance

LEPII, Tevatron, LHC access scales greater than $\Lambda \sim 10$ TeV

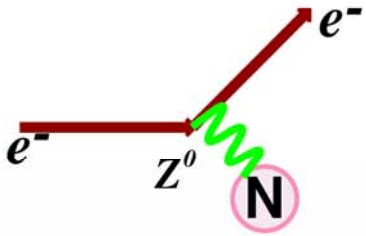
$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g\, G_F} \longrightarrow \boxed{\begin{array}{l} \delta(g)/g \sim 0.1 \\ \Lambda \sim 10\ \text{TeV} \end{array}}$$

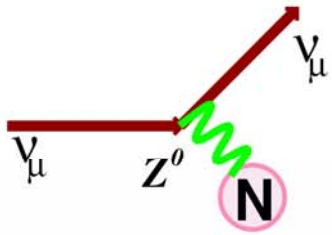
$$\frac{\delta(\sin\theta_W)}{\sin^2\theta_W} \lesssim 0.01$$

Weak Neutral Current at low Q^2



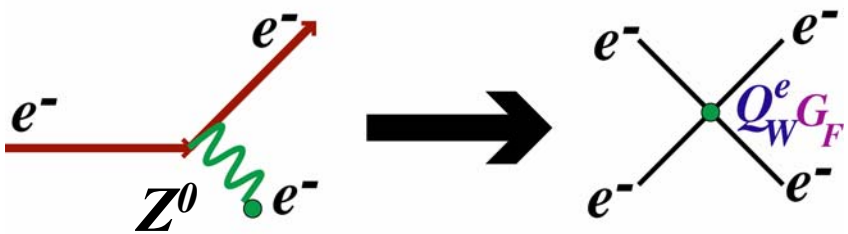
statistics





hadronic physics

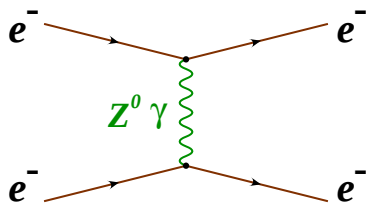
atomic wave function

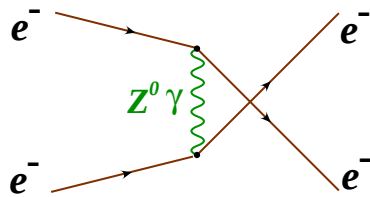


Purely leptonic reaction

$$Q^e_W \sim 1 - 4\sin^2\theta_W$$

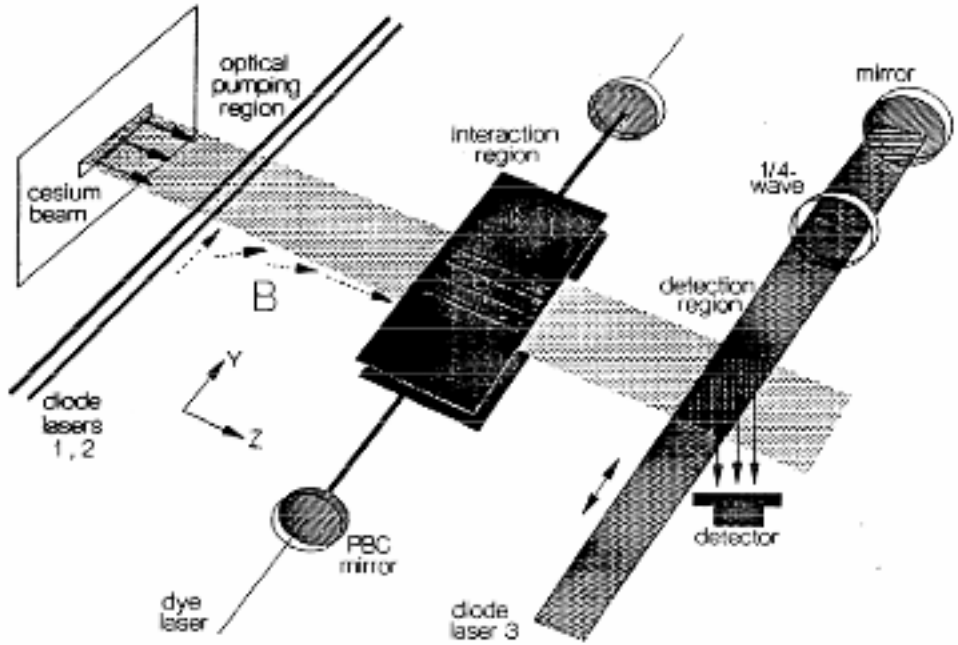
Fixed Target Møller Scattering

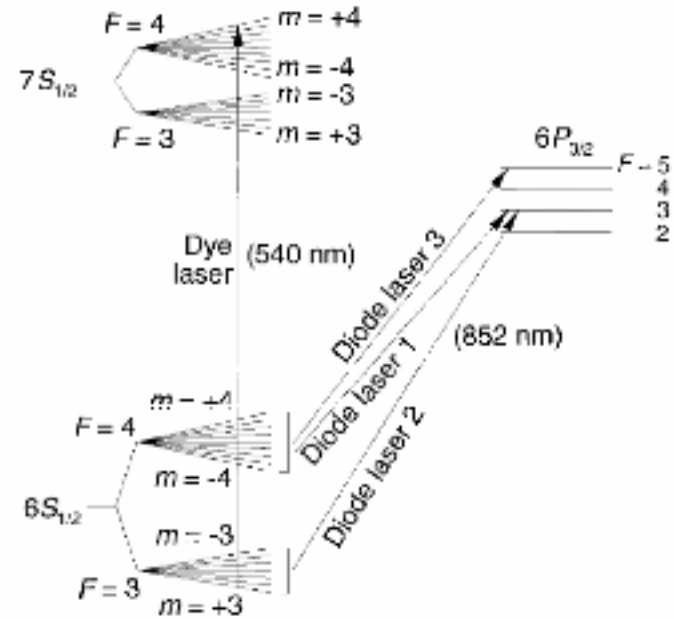




APV: Boulder Cs Experiment

(1982 -1997)



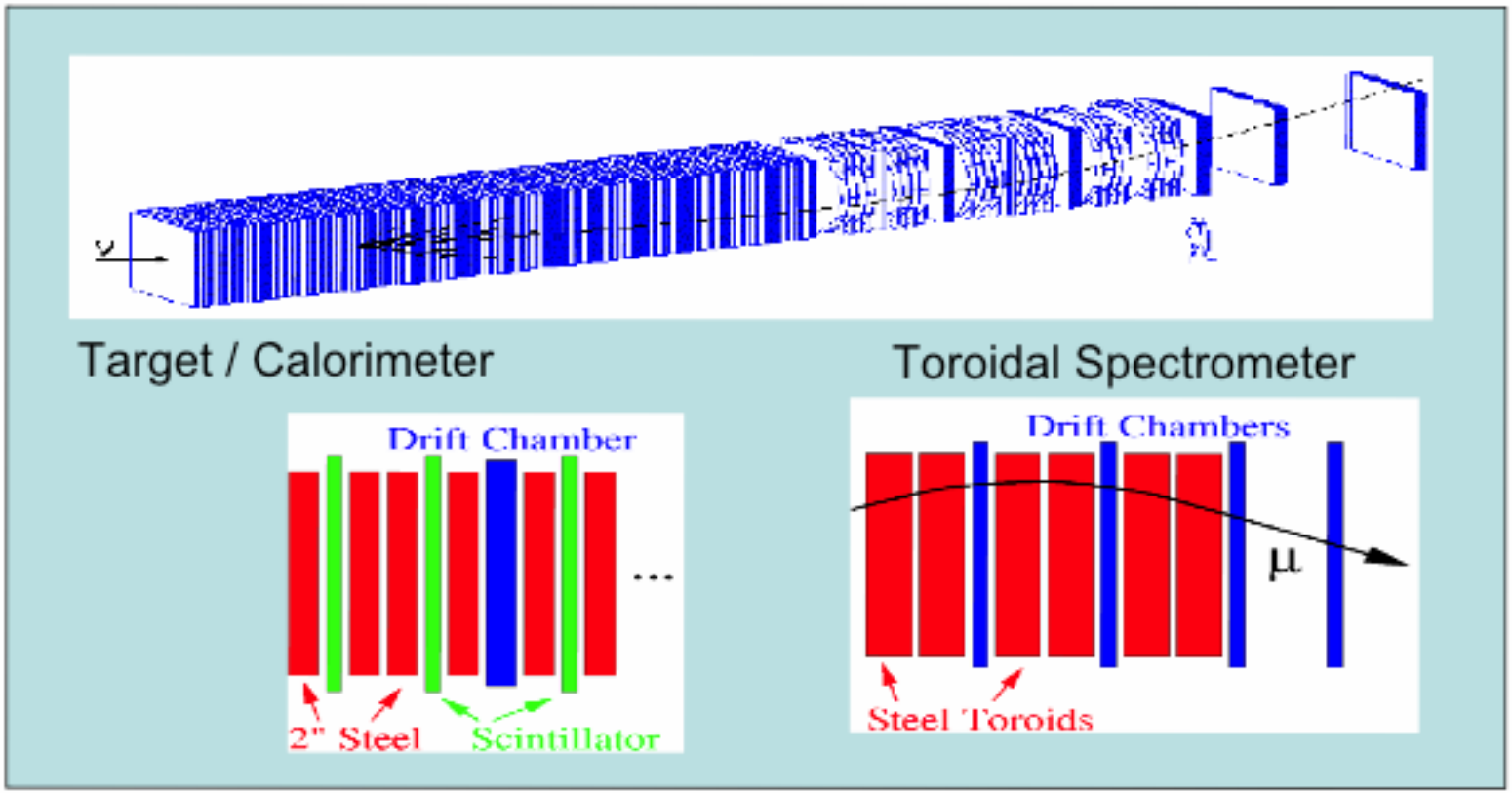


- measure APV component of $6s \rightarrow 7s$ transition in ^{133}Cs ; interferes with E1 (Stark) transition
- 5 reversals to isolate APV signal and suppress systematics
- APV signal is ~ 6 ppm of total rate, measured to 0.7% (40 ppb!)

$$Q_W = -N + Z\left(1 - 4\sin^2\theta_W\right)$$

$$Q_W\left(^{133}\mathrm{Cs}\right) = -72.74 \pm 0.29\,(\mathrm{expt}) \pm 0.36\,(\mathrm{theory})$$
$$= -73.19 \pm 0.13 \quad (\mathrm{SM})$$

NuTeV Neutrino Experiment



$$R^{-} = \frac{\sigma_{\nu N}^{NC} - \sigma_{\bar{\nu} N}^{NC}}{\sigma_{\nu N}^{CC} - \sigma_{\bar{\nu} N}^{CC}} \approx \rho^{2}\left(\frac{1}{2} - \sin^{2}\theta_{W}\right)$$

$$\sin^{2}\theta_{W}^{(on-shell)} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)$$

Standard Model prediction is 0.2227 (3σ deviation)

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.*

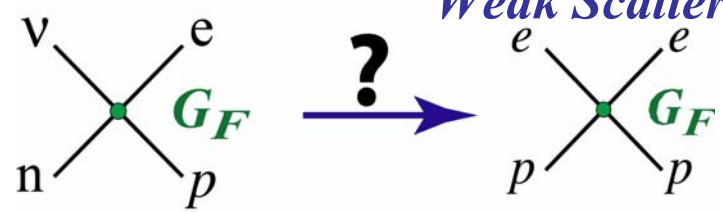
Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine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

Phys

Neutron β Decay

Electron-proton Weak Scattering

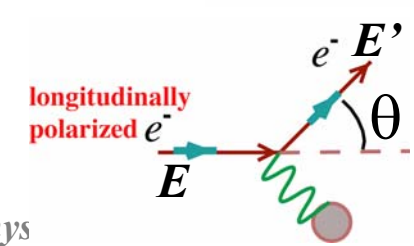


$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

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

Parity-violating

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



4-momentum transfer

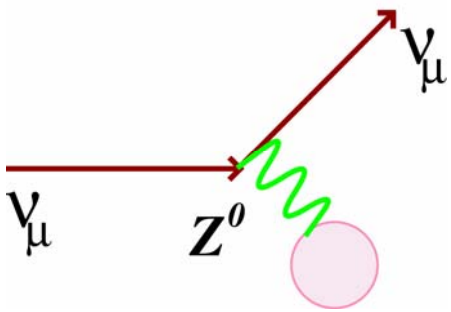
$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

Weak Electromagnetic Interference

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.

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

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



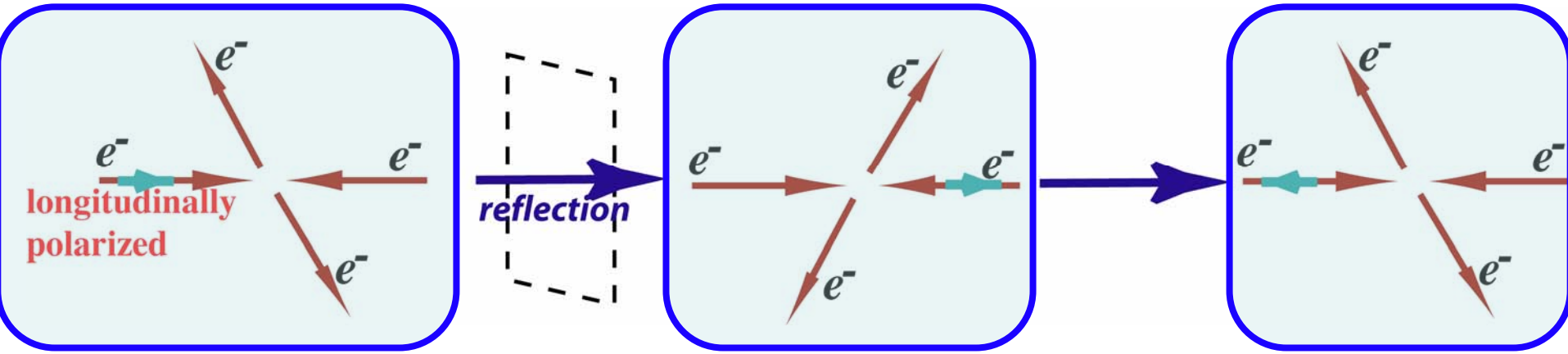
Many new theories (other than SU(2) X U(1)) predicted weak neutral currents, but many cases had no interference predicted.

Neutral weak force first measured in the early '70s: $\sin^2\theta_W \sim 1/4$

Do the weak and electromagnetic amplitudes interfere?

A critical test for the correct gauge structure of the theory

Accessing Parity Violation

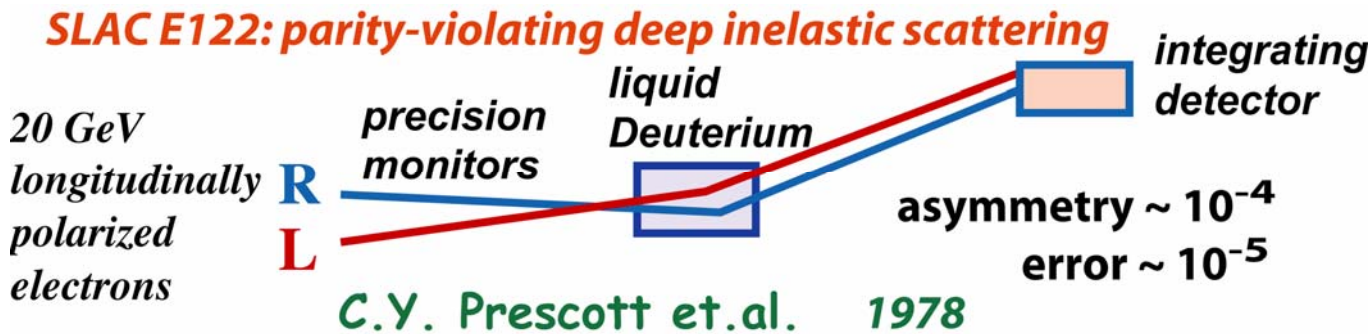


- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

Observation of Weak-Electromagnetic Interference

It was realized independently in the mid 70s at SLAC:

A_{PV} in Deep Inelastic Scattering off liquid Deuterium: $Q^2 \sim 1\ (GeV)^2$



- *Established the basic experimental technique*
- *Cleanly observed weak-electromagnetic interference*
- *Parity Violation in Weak Neutral Current Interactions*
- *$\sin^2\theta_W = 0.224 \pm 0.020$: same as in neutrino scattering*

E158 at SLAC

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

At the Stanford Linear Accelerator Center

E158 Collaboration

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

8 Ph.D. Students
60 physicists

E158 Chronology

Sep 97: 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: Final publications

Tiny Asymmetry

Imagine measuring the length of Central Park in NYC with 2 different meter scales: answer is expected to differ by 1 mm!

Highest electron beam energy with longitudinal beam polarization:

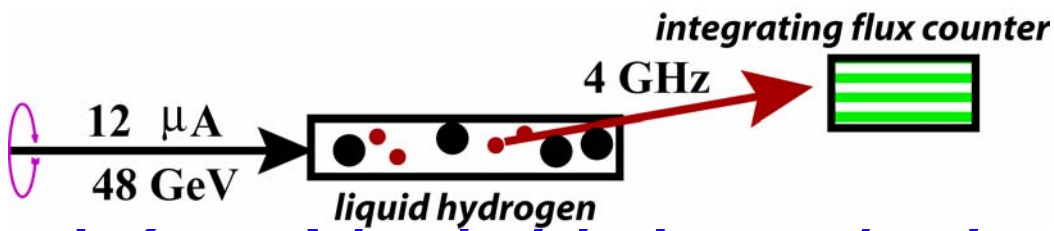
50 GeV at the Stanford Linear Accelerator Center

Raw asymmetry ~ 1 x10^{-7} (100 ppb)

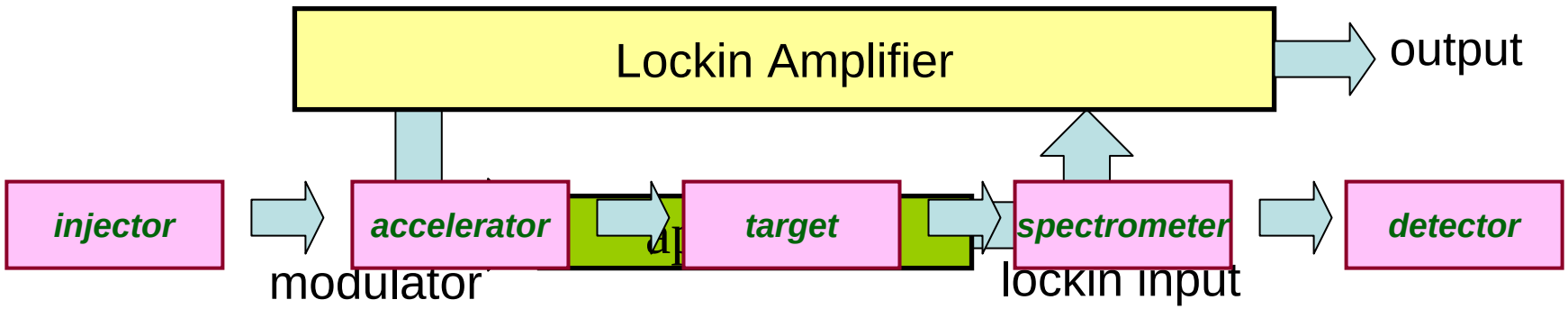
$\delta(A_{PV})$ ~ 10^{-8} (10 ppb)

Need 10^{16} events

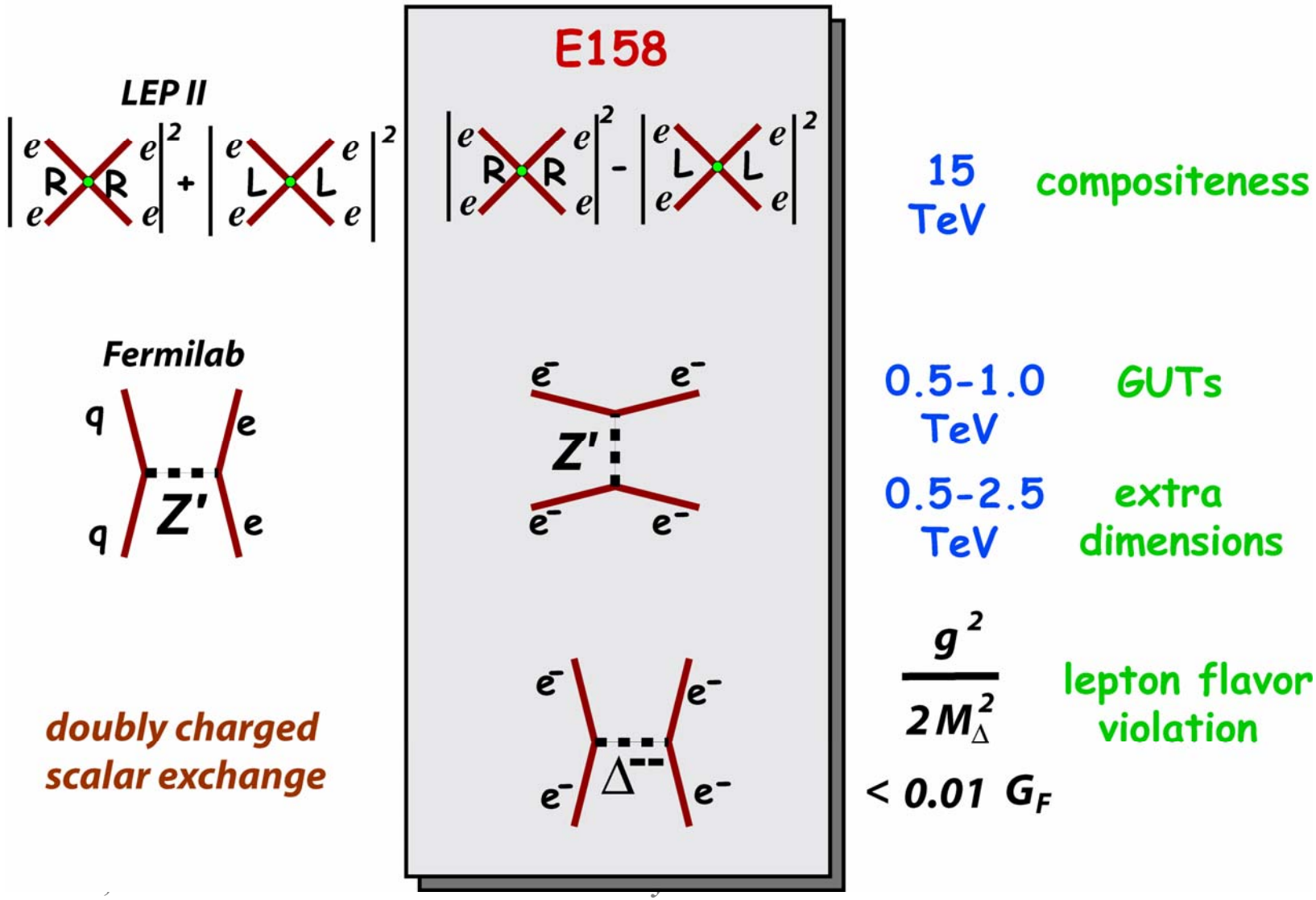
Count at ~ 1 GHz



Tiny signal (weak force) buried in known background (QED)



E158 New Physics Reach

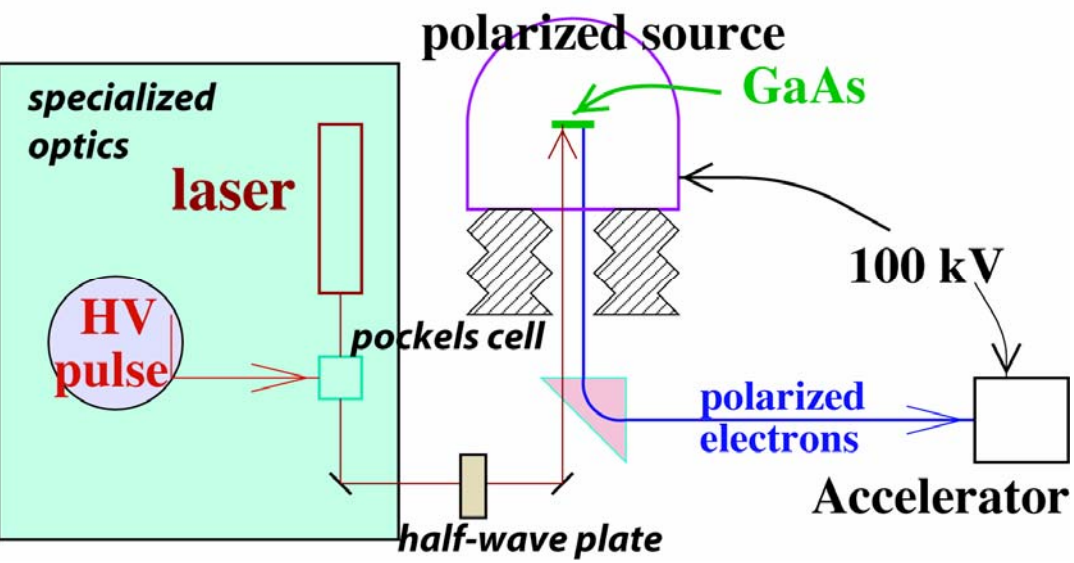


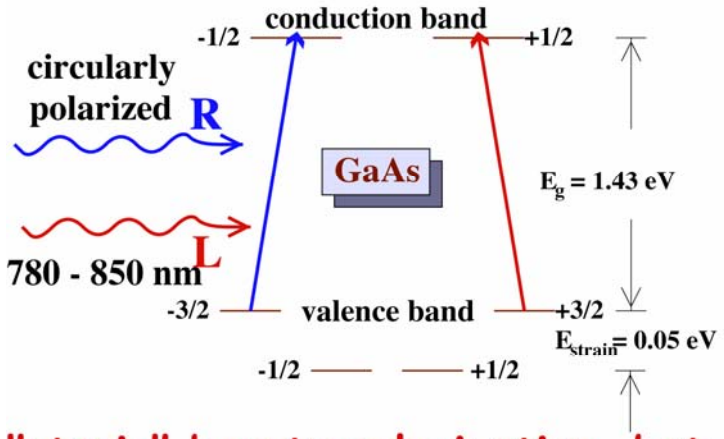
Optical Pumping

Modulate longitudinal polarization of the electron beam

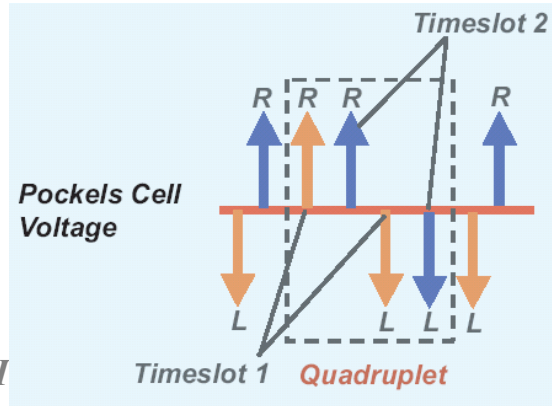
✧ ***Beam helicity is chosen pseudo-randomly at 120 Hz***

- *sequence of pulse quadruplets*
- *Data analyzed as "pulse-pairs"*



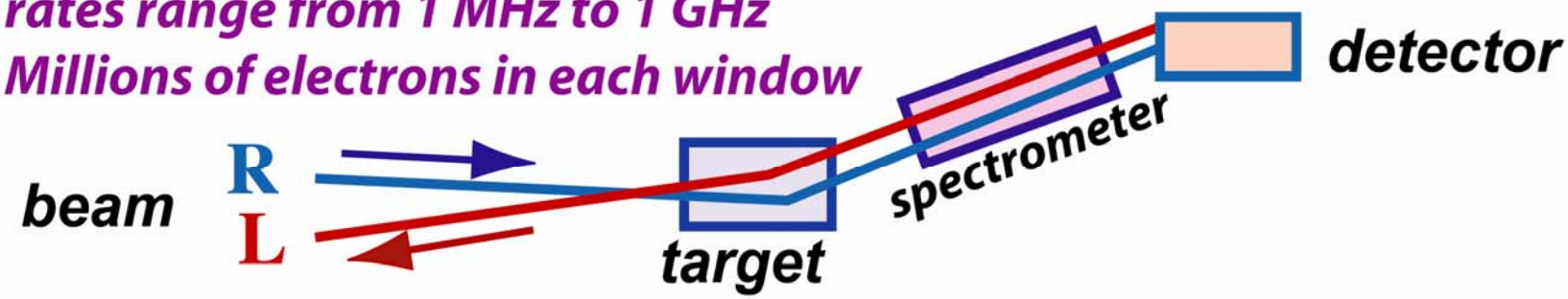


"strain" boosts polarization, but introduces anisotropy in response



Experimental Technique

- rates range from 1 MHz to 1 GHz
- Millions of electrons in each window

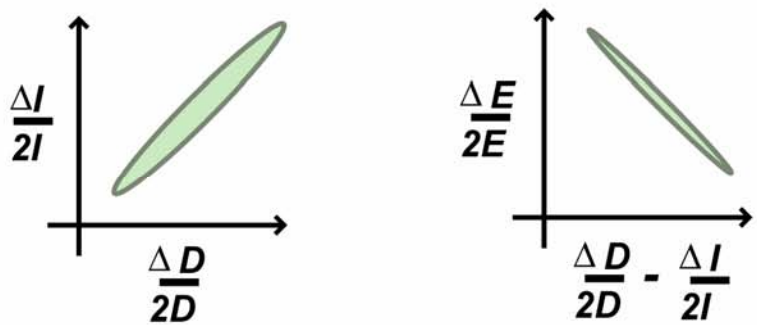


Detector D, Current I: $F = D/I$

$$A_{pair} = \frac{F_R - F_L}{F_R + F_L}$$

* Rapid helicity flip with each window
* Spatially separate signal
* Integrate scattered flux
* control beam jitter

$$A_{pair} = \frac{\Delta F}{2F} + \Delta A\,(X, Y, \vartheta_X, \vartheta_Y, E)$$



each window-pair measures A_{PV} with variance ~ $\frac{1}{\sqrt{2 \bullet N_{window}}}$

E158 ⇒ $\frac{200\ ppm}{\sqrt{320\ M}} = 11\ ppb$

Systematic Control

Detector D, Current I: F = D/I

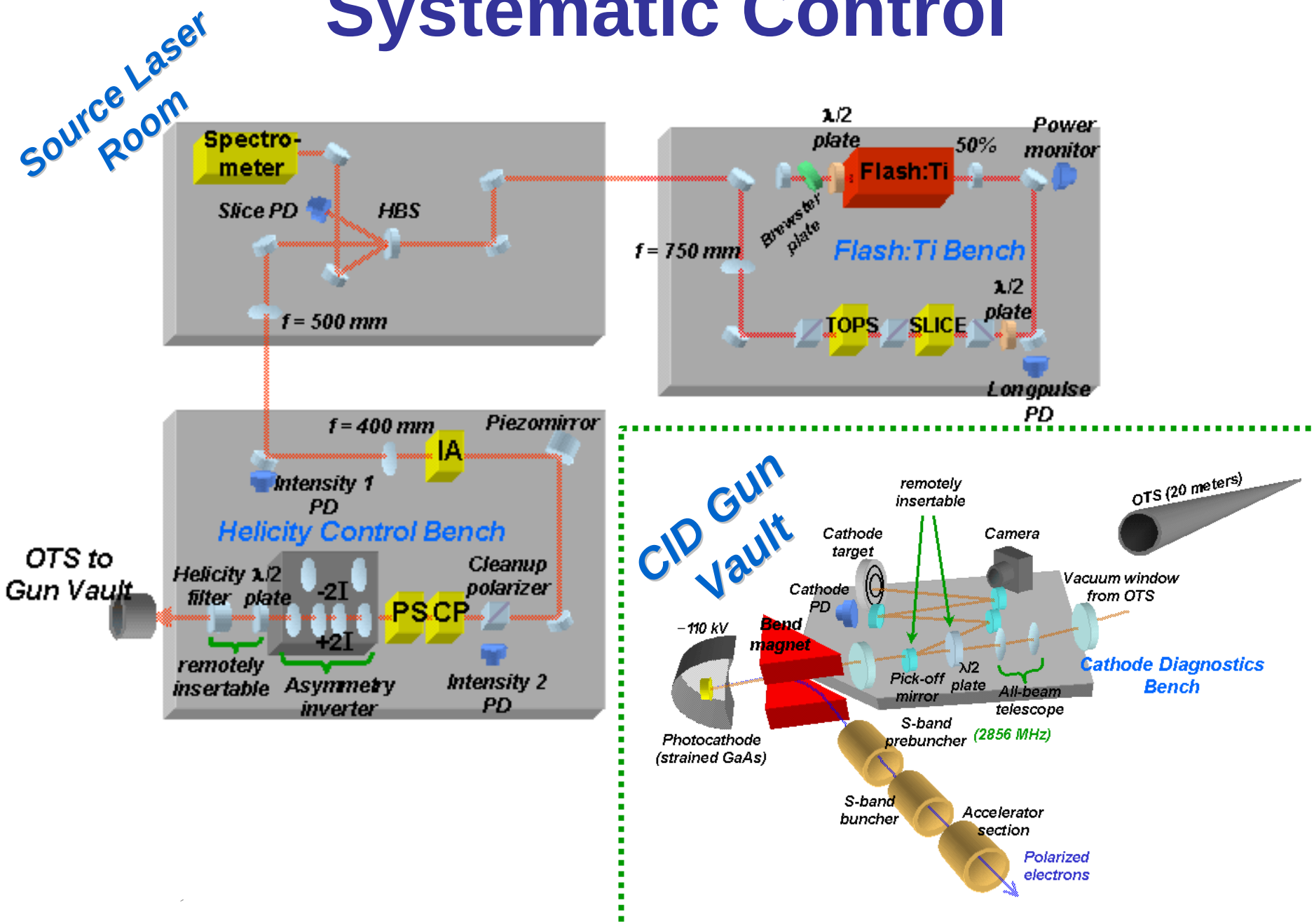
$$A_{pair} = \frac{F_R - F_L}{F_R + F_L} = \frac{\Delta F}{2F} + \textit{fluctuations}$$

$$A_{pair} \cong \frac{\Delta D}{2D} - \frac{\Delta I}{2I} + \frac{\Delta E}{2E} + \alpha_i \Delta X_i$$

jitter (ppm)	200	5000	1000	500	linac tune
accuracy (ppm)		30	30	50	
cumulative (ppb)	110 +/-11	200 +/-1	20 +/-2	20 +/-2	

→ *precision monitoring and control of electron beam fluctuations*

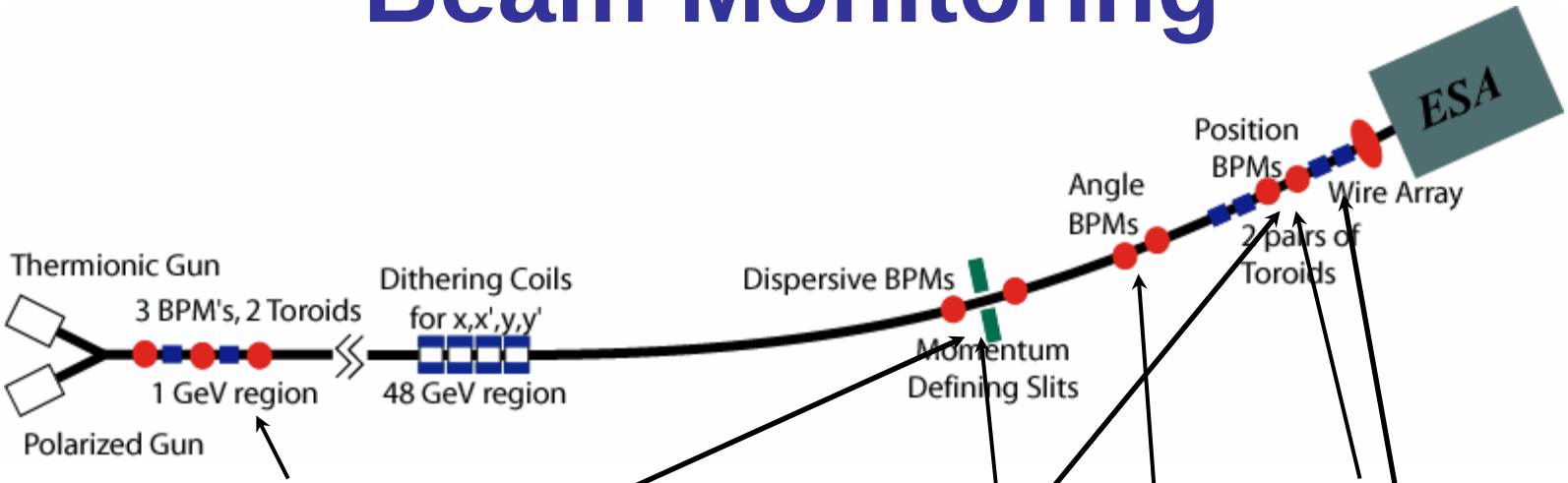
Systematic Control



Experimental Apparatus

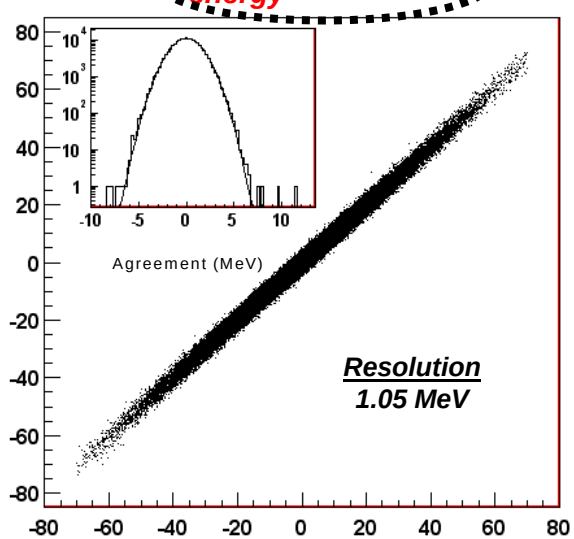
- Polarized Beam
- Precision Beam Monitoring
- Liquid Hydrogen Target
- Spectrometer
- Detectors

Beam Monitoring

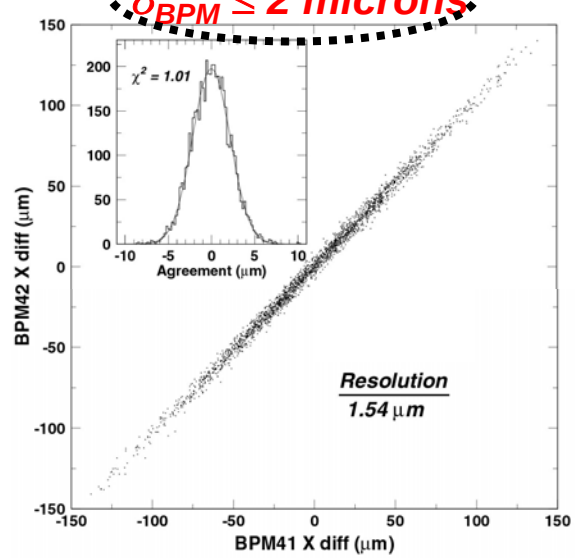


Pulse by pulse monitoring at 1 GeV and 45 GeV

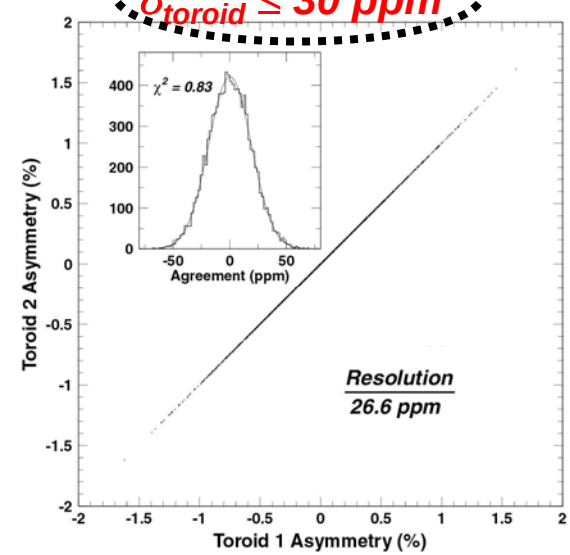
$\sigma_{energy} \leq 1$ MeV



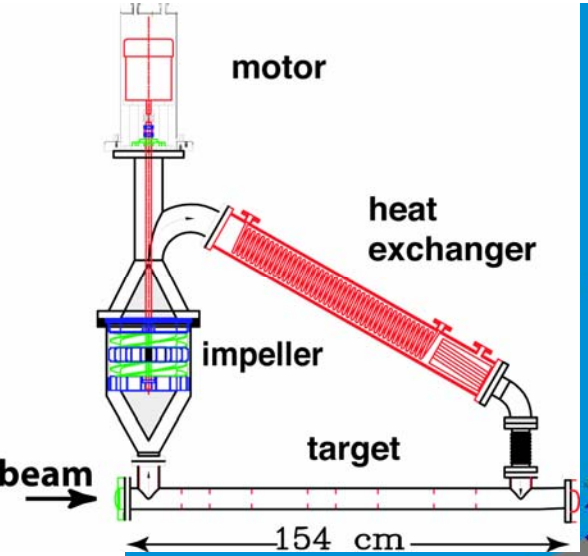
$\sigma_{BPM} \leq 2$ microns

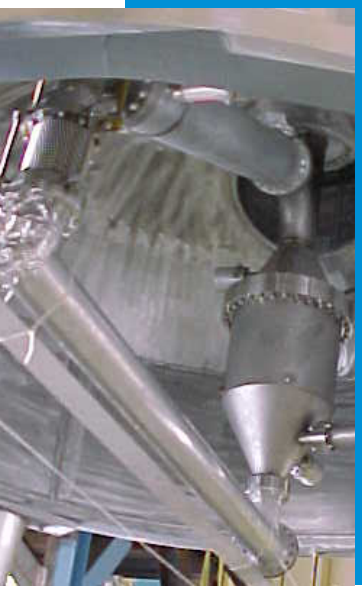


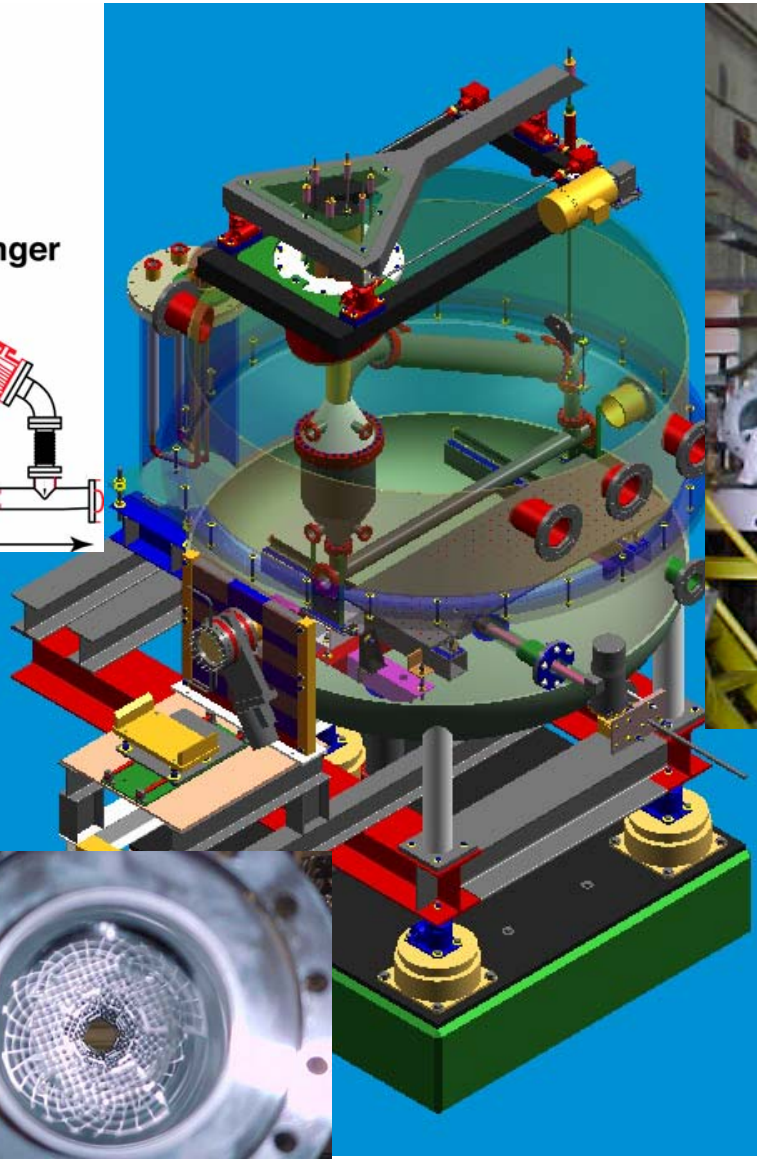
$\sigma_{toroid} \leq 30$ ppm



Liquid Hydrogen Target

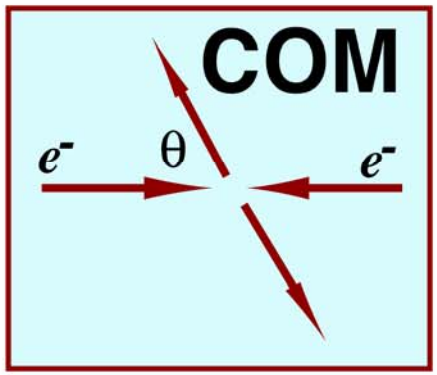


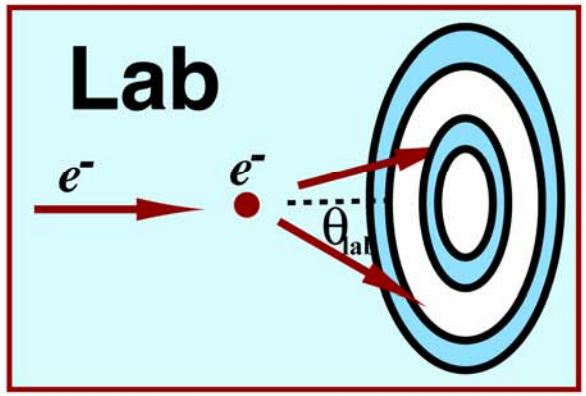


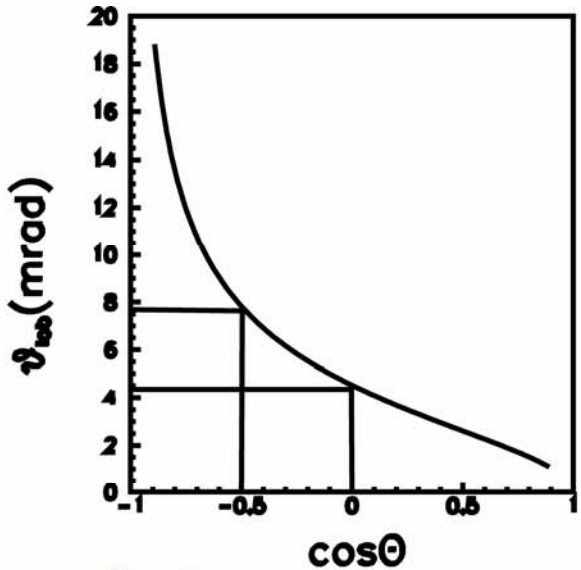


Refrigeration Capacity	*1 k*
Operating Temperature	*20*
Length	*1.5*
Flow Rate	*5 m*
Vertical Motion	*6 inch*

Kinematics

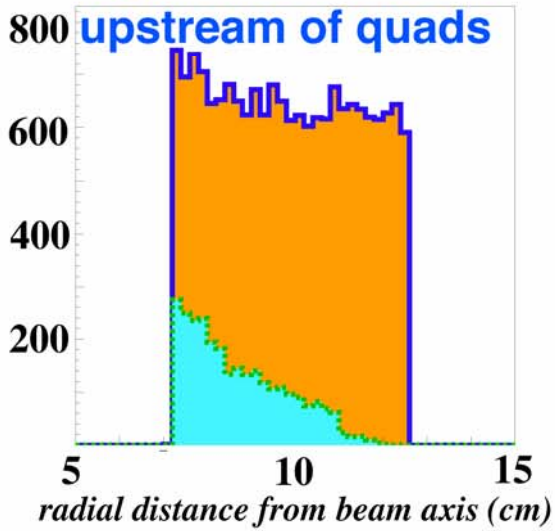


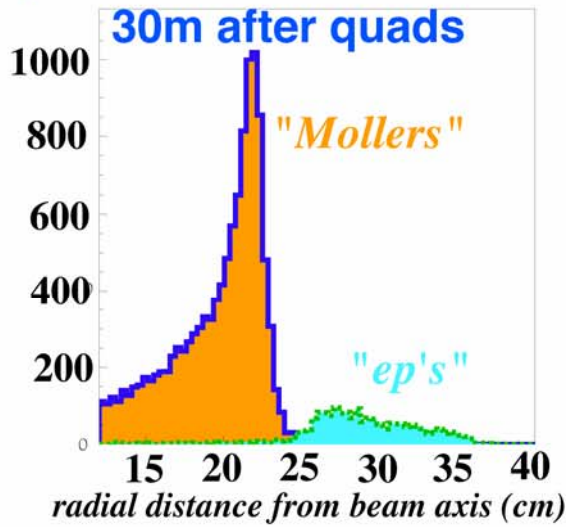




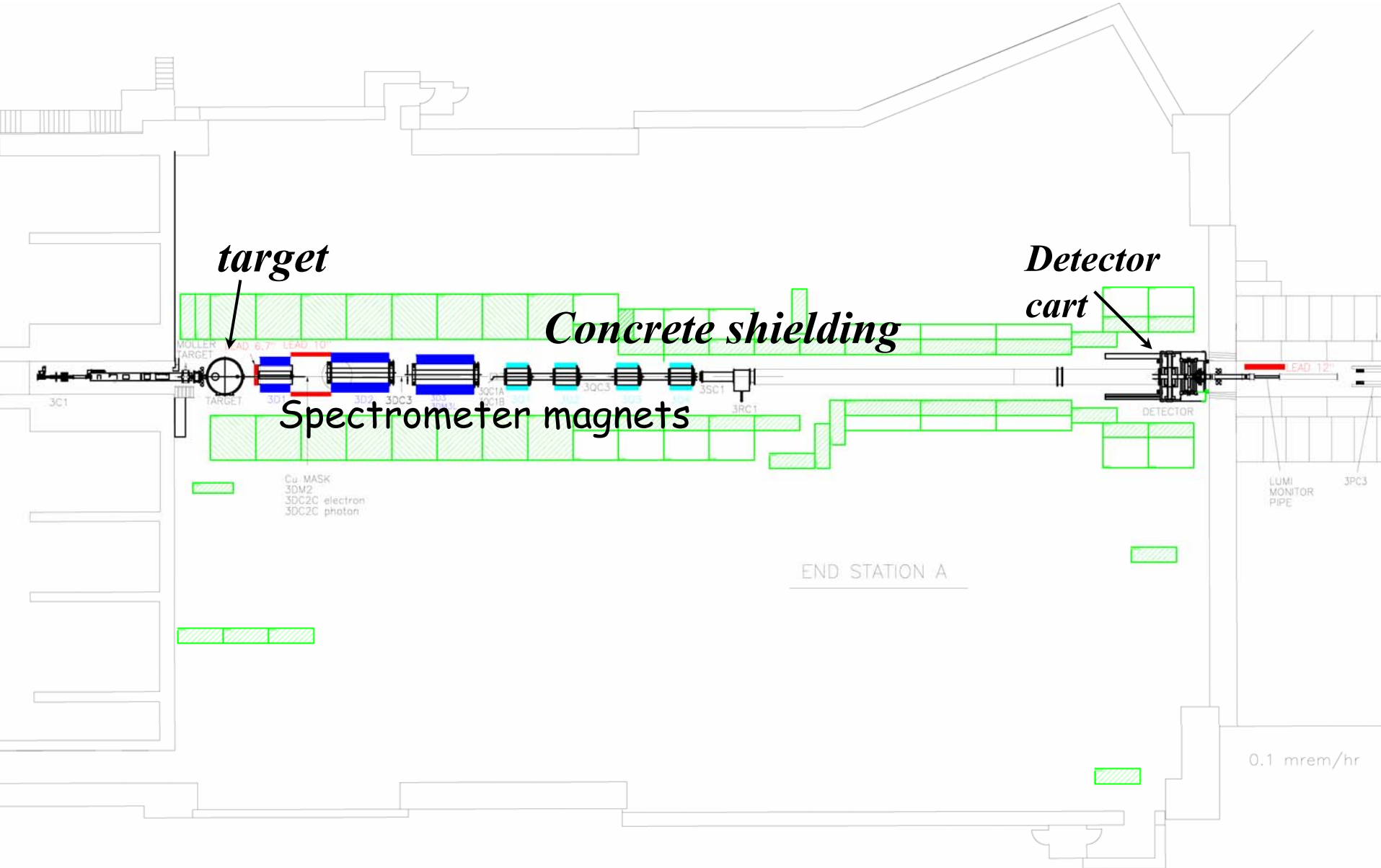
Quadrupole Quadruplet

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





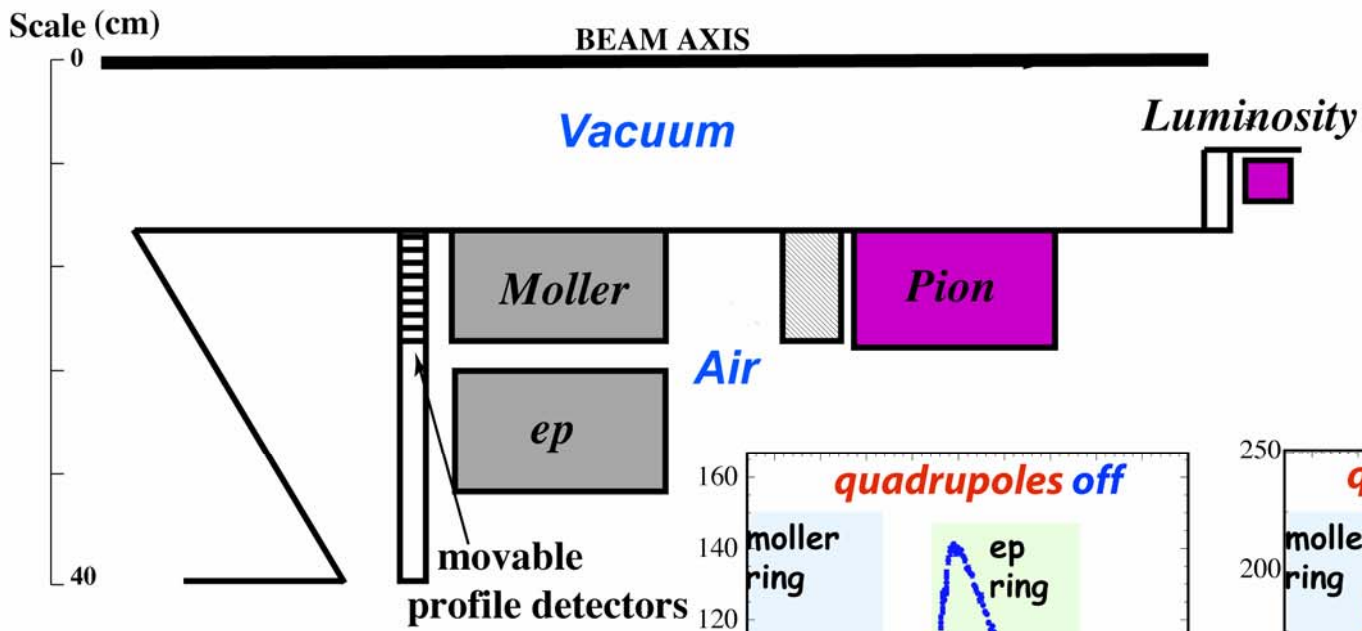
E158 Plan View in ESA

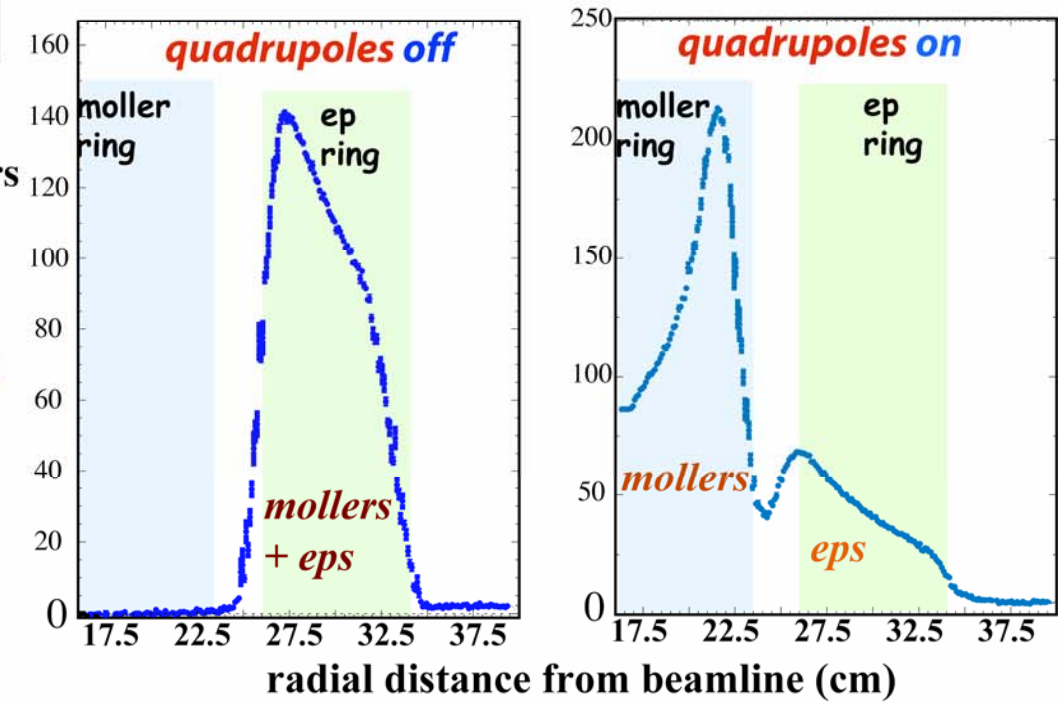


E158 Spectrometer

Downstream Configuration

Detector Concept

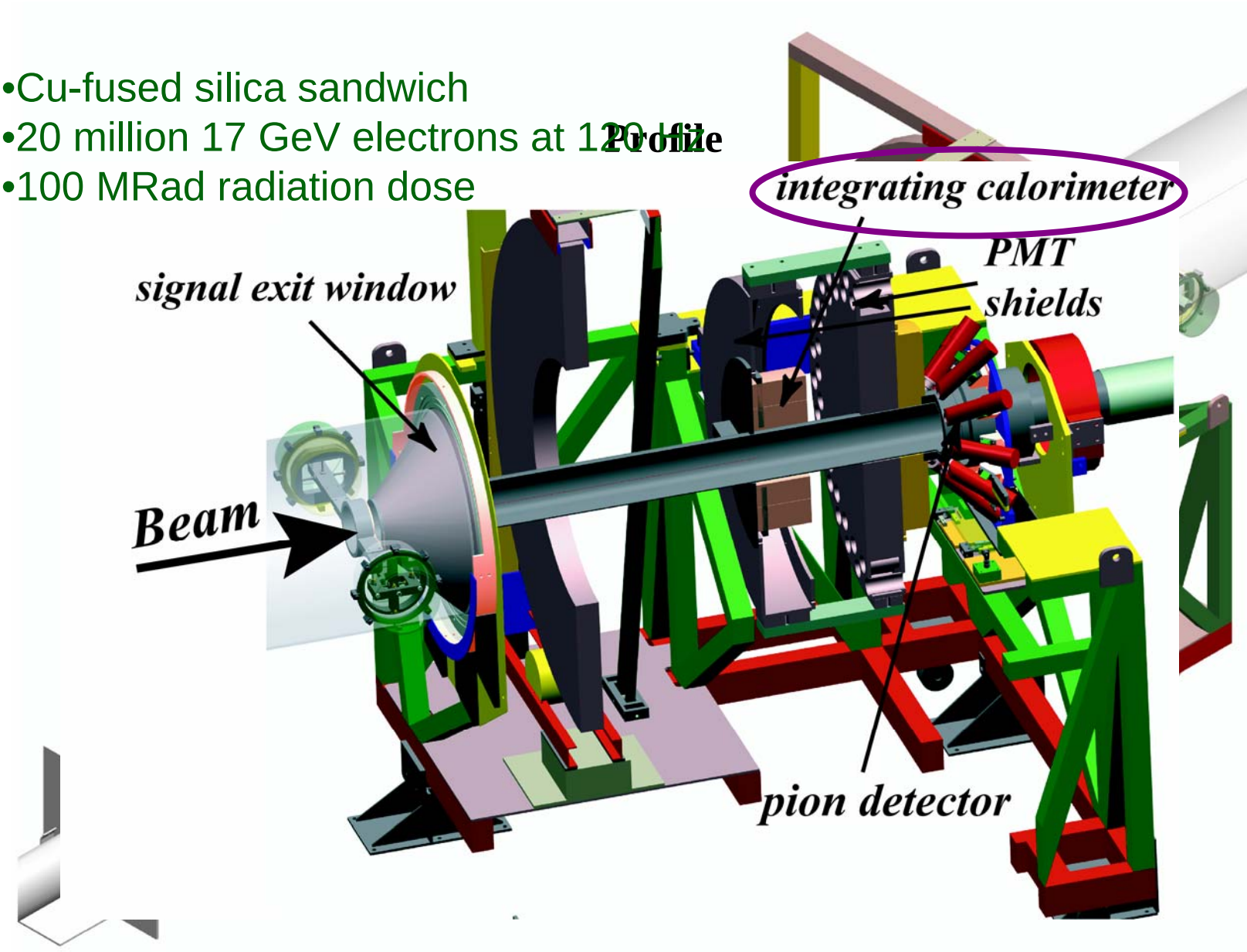




* 4 integrating detectors
* profile detectors for calibration

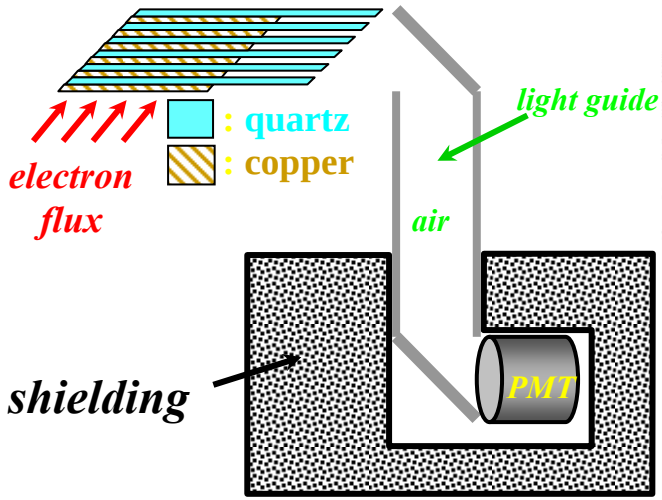
Detector Cart

- Cu-fused silica sandwich
- 20 million 17 GeV electrons at 120 Hz
- 100 MRad radiation dose

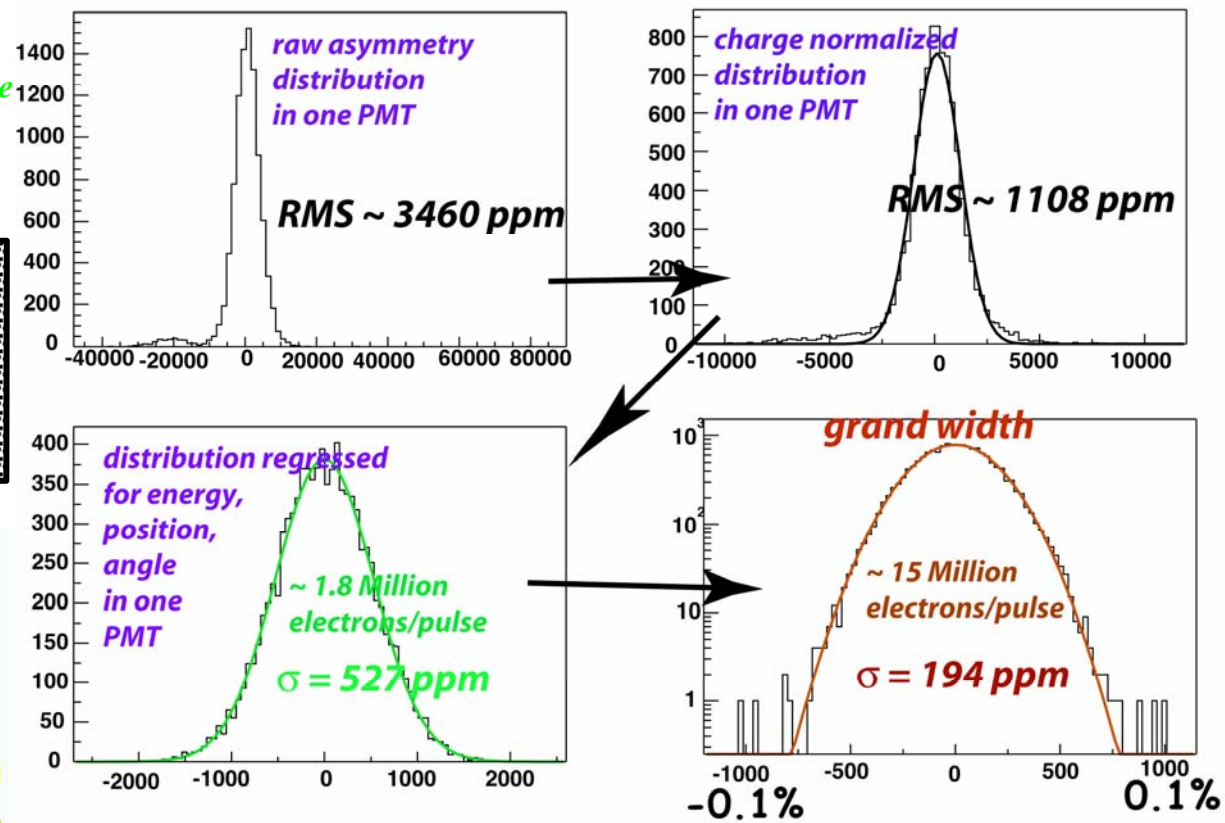


Analysis of Calorimeter Response

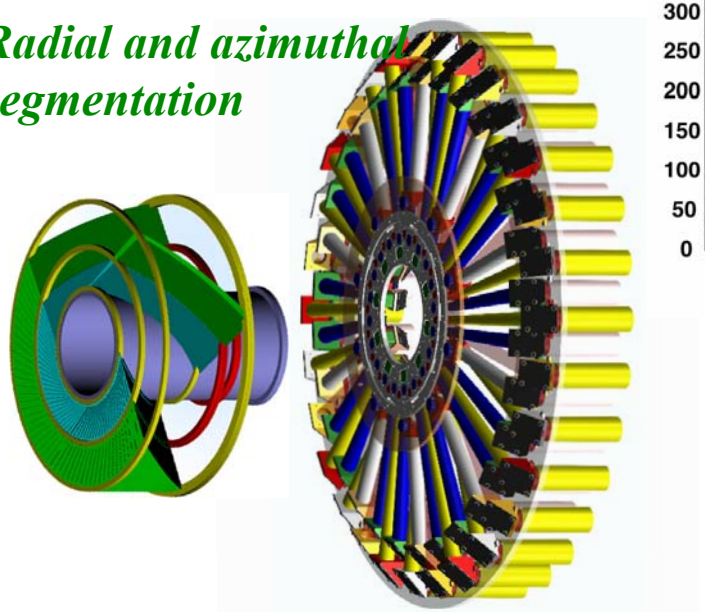
Basic Idea:



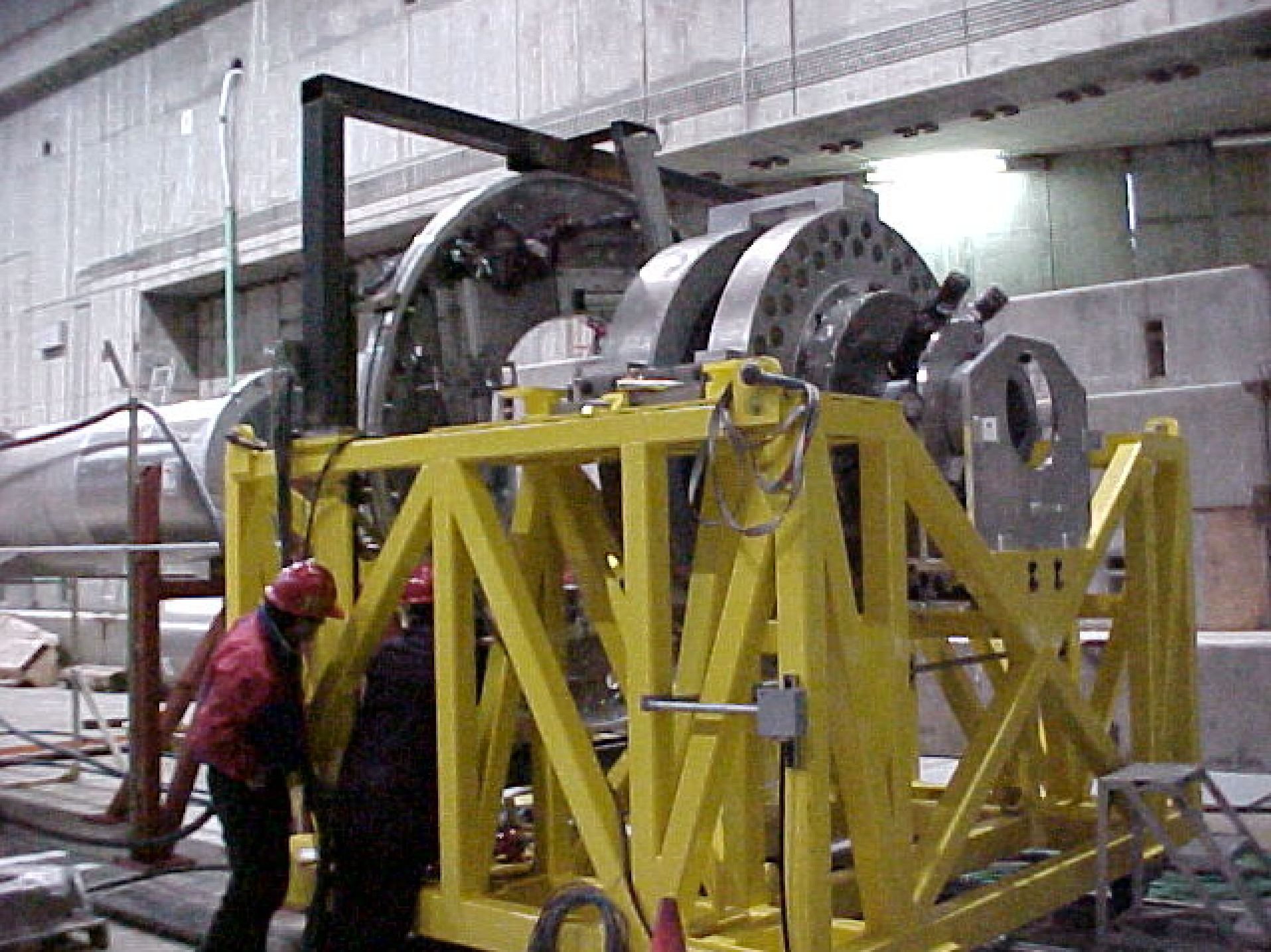
observed left-right asymmetry distribution



Radial and azimuthal segmentation

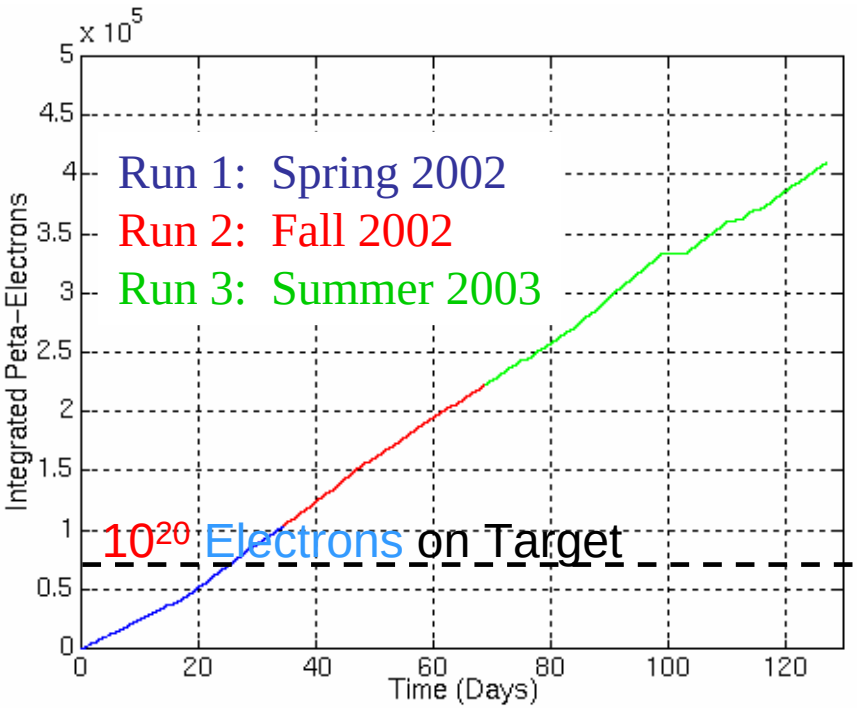


- Corrections for beam fluctuations
- Average over runs
- Statistical tests
- Beam polarization and other normalization

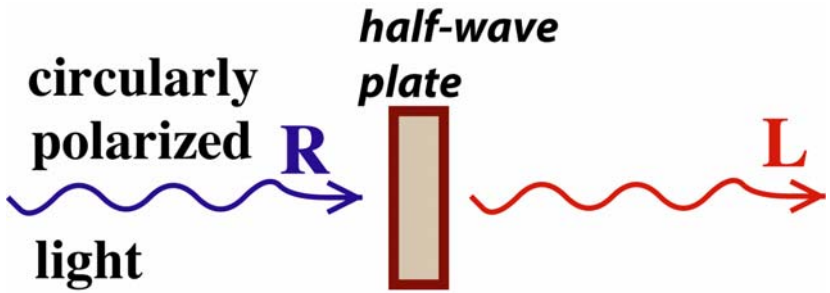


Physics Runs

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



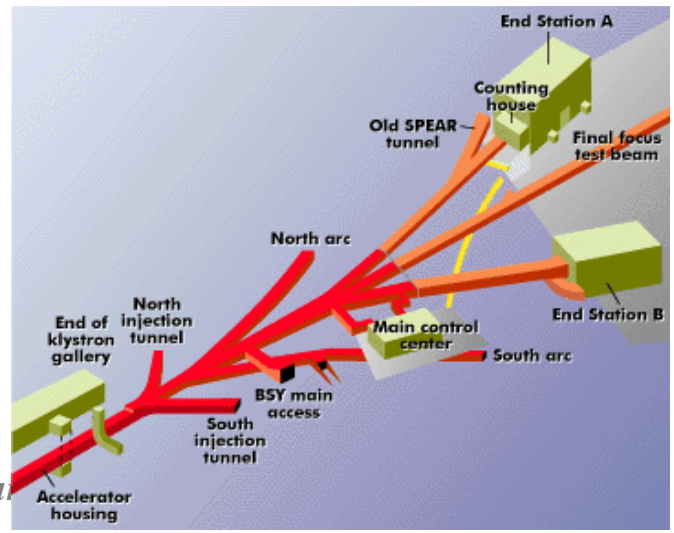
A_{PV} Sign Flips



g-2 spin precession

45 GeV: 14.0 revs

48 GeV: 14.5 revs

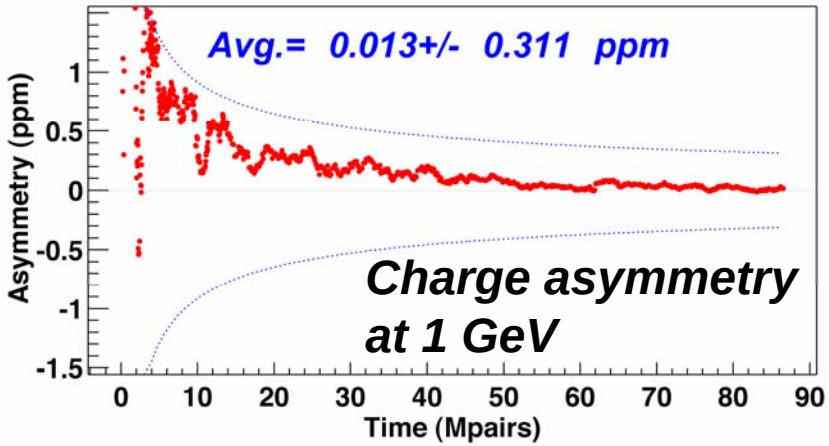


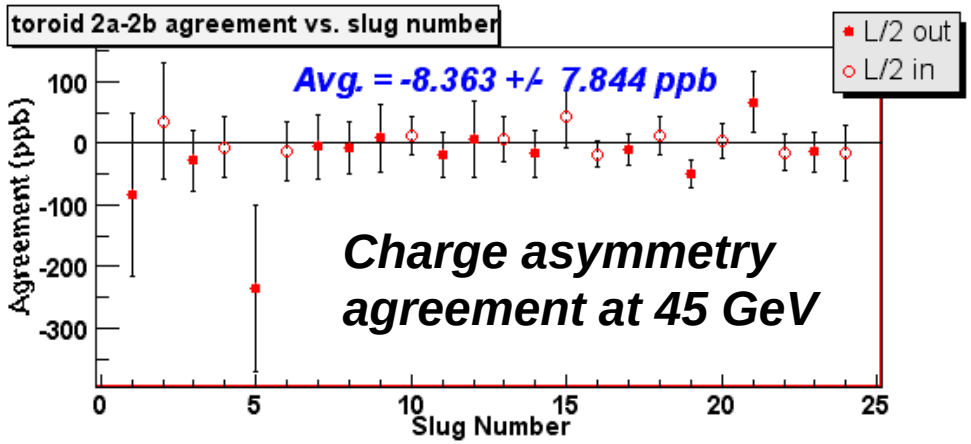
Data divided into 75 "slugs":

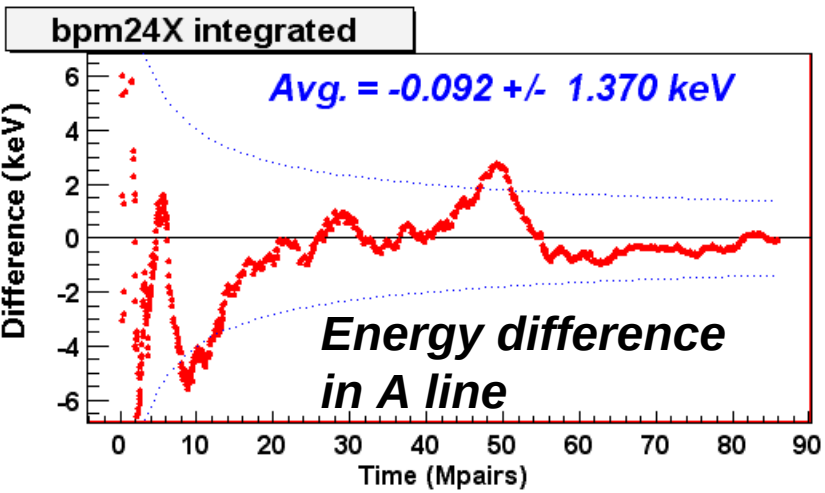
- Wave plate flipped ~ few hours

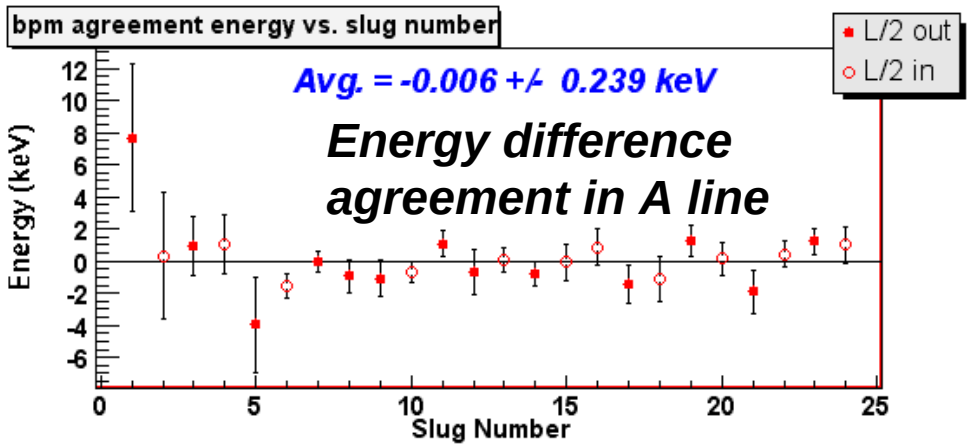
- Beam energy changed ~ few days

Beam Asymmetries



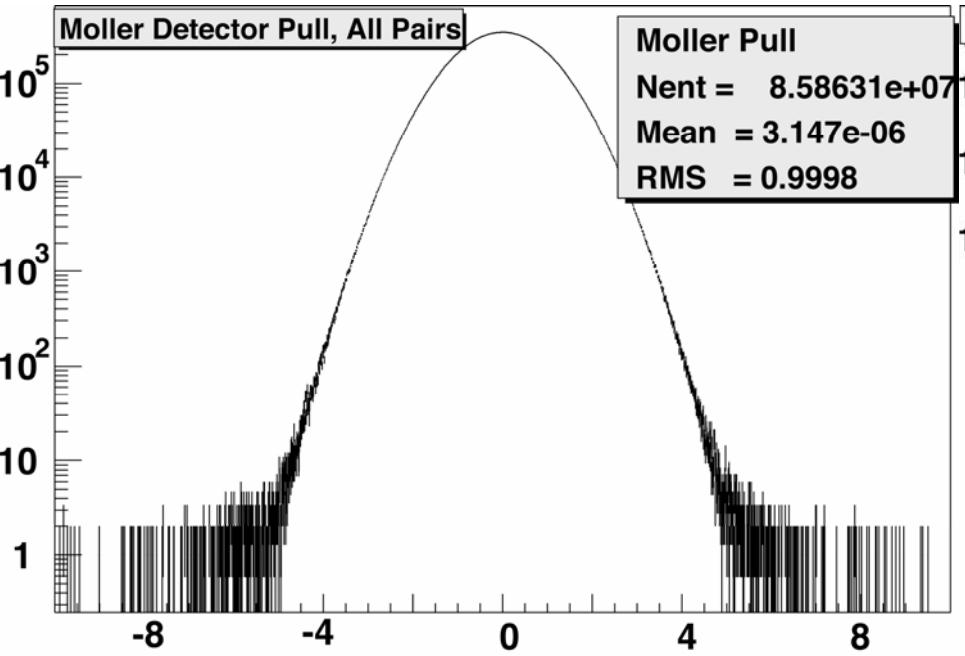


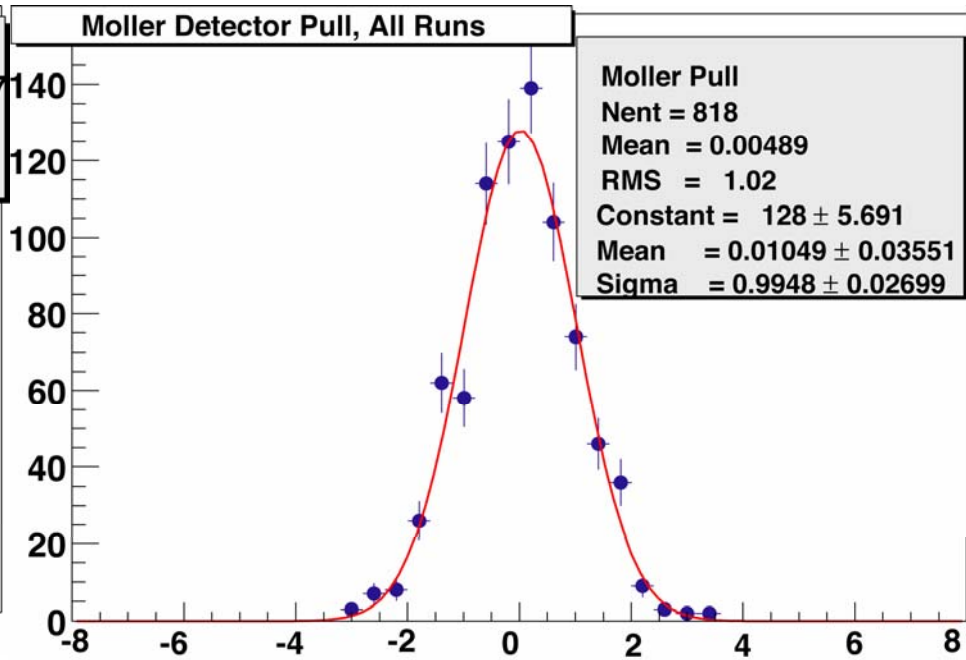




Position differences < 20 nm ***Position agreement ~ 1 nm***

Raw Asymmetry Statistics





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

$\sigma_i \approx 200$ ppm

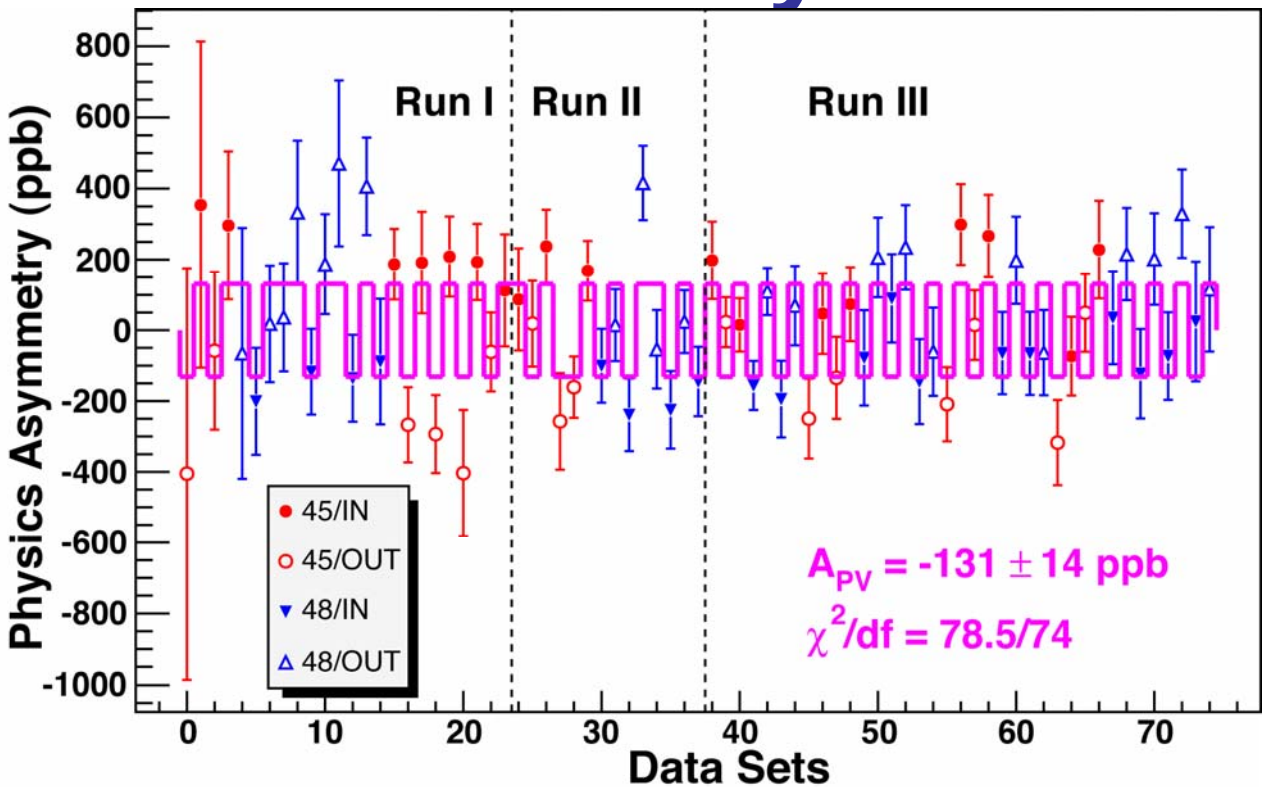
$N = 85$ Million

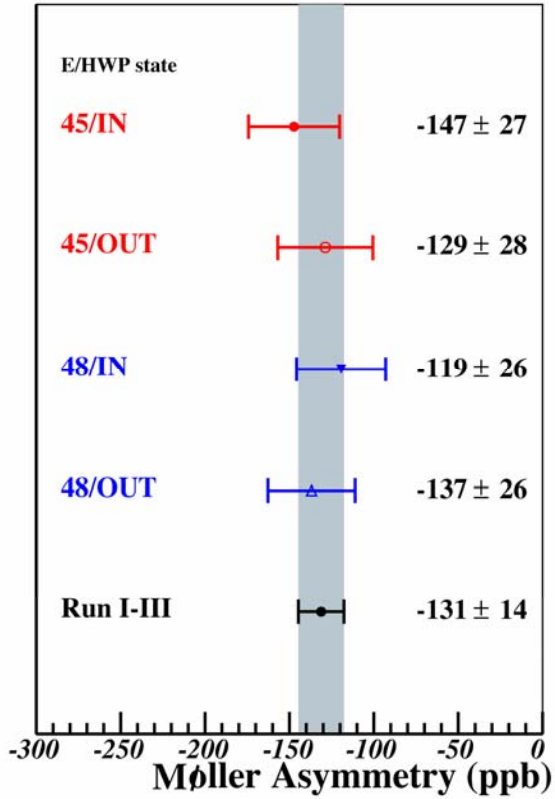
$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

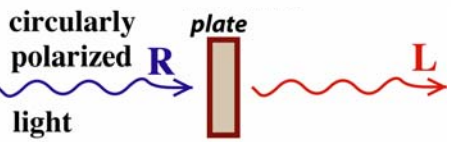
$\sigma_i \approx 600$ ppb

$N = 818$

Final Analysis of All 3 Runs



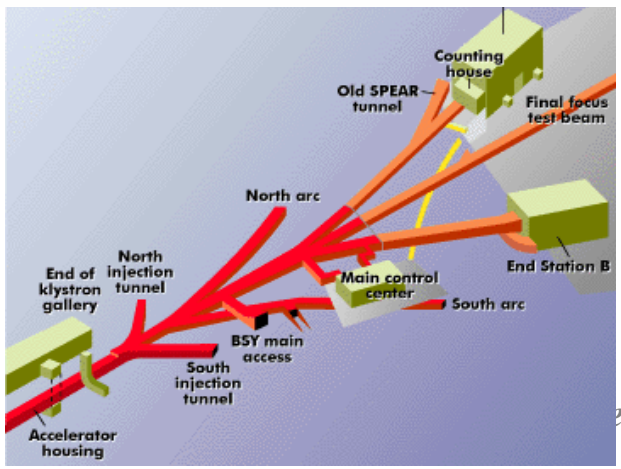




g-2 spin precession

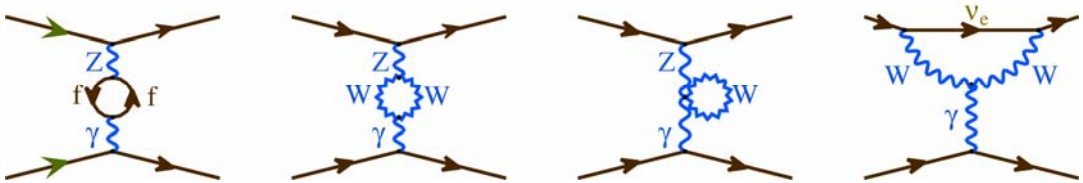
45 GeV: 14.0 revs

48 GeV: 14.5 revs

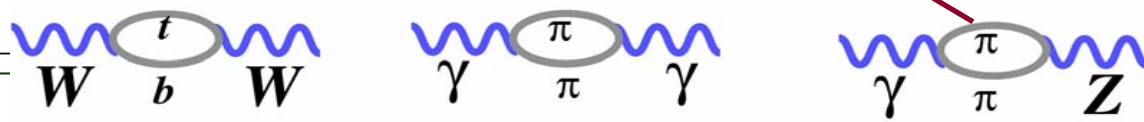


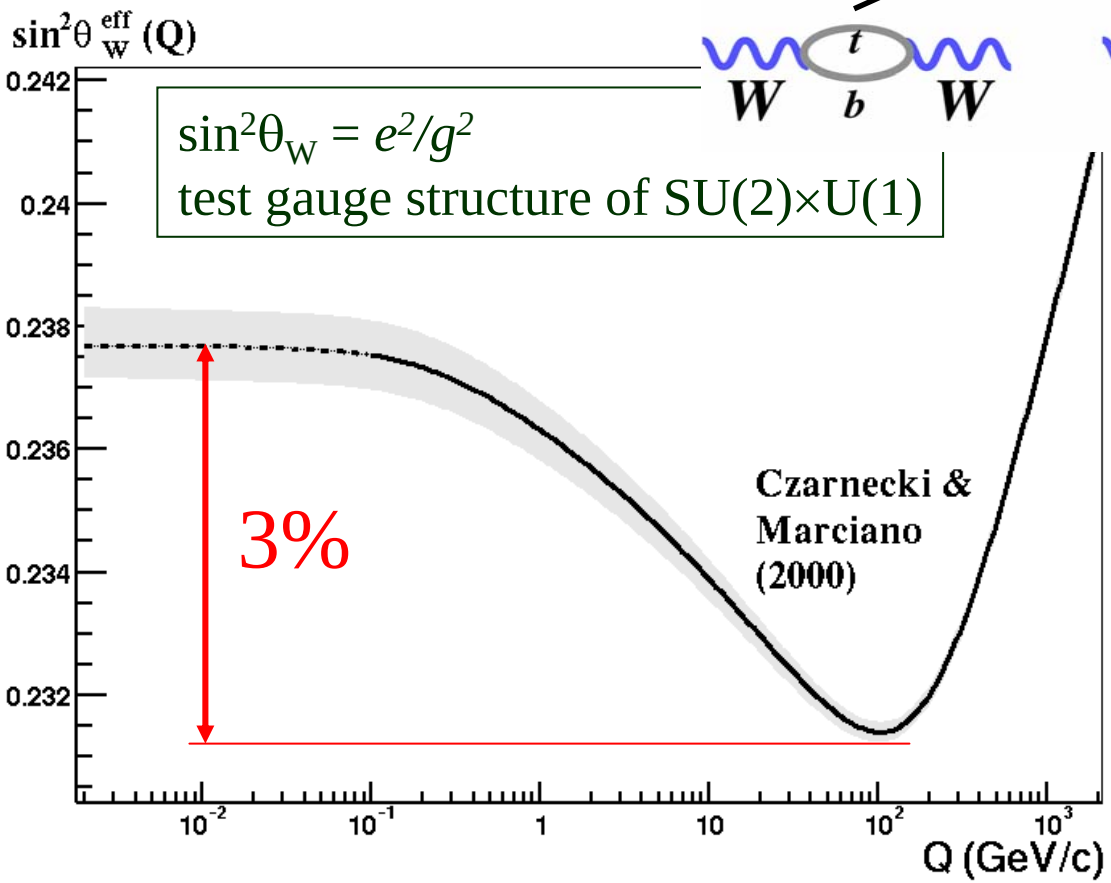
$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

Electroweak Physics



$$\frac{1}{2} - q \sin^2 \theta_W$$



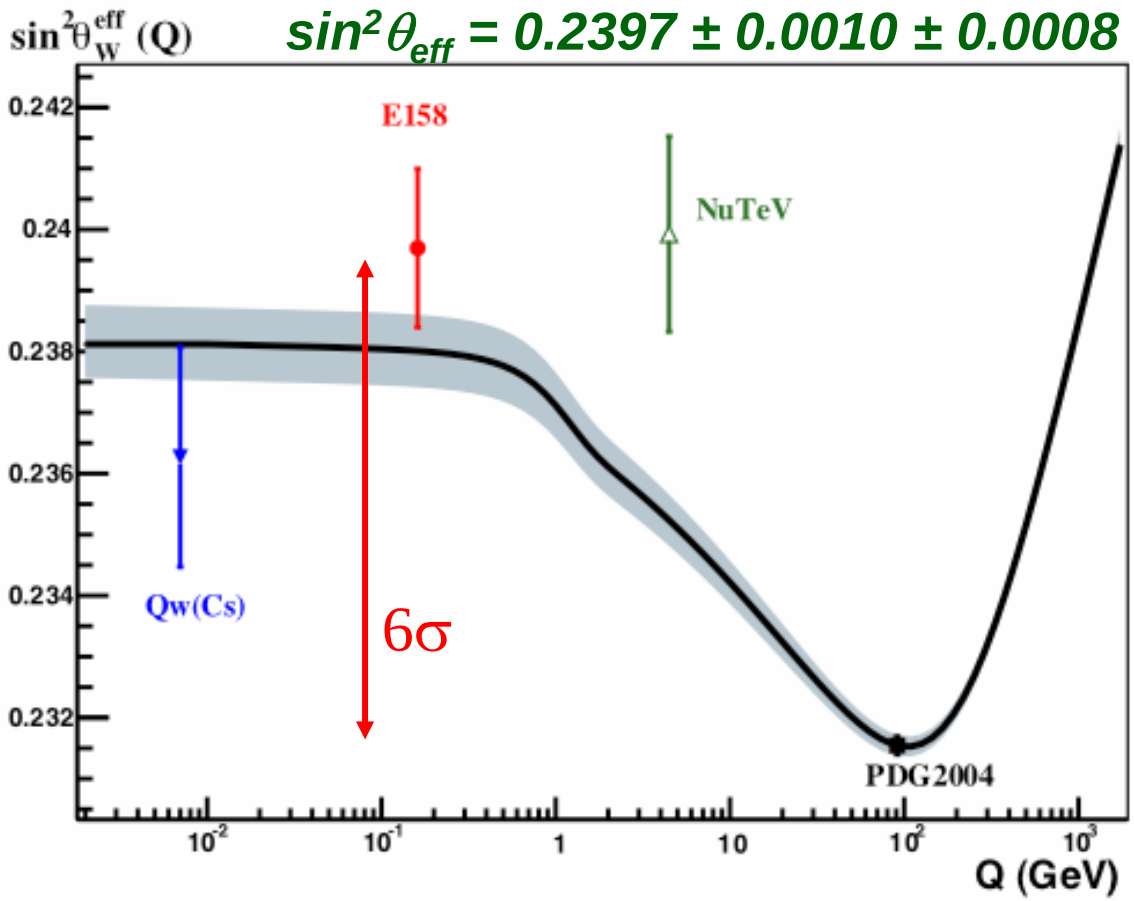


$\sin^2\theta_W = e^2/g^2$

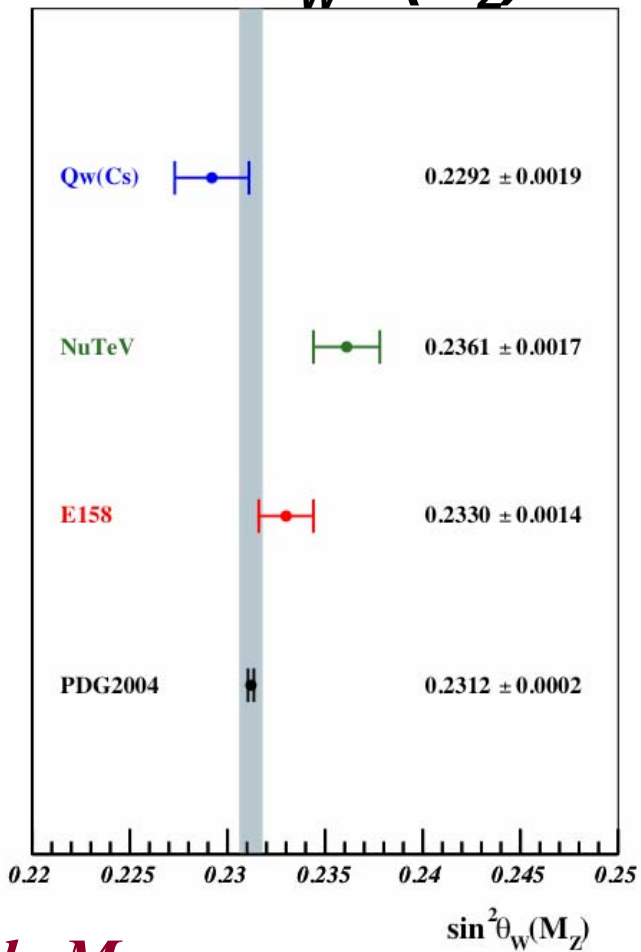
test gauge structure of SU(2)×U(1)

Final Physics Results

$\sin^2\theta_{eff} = 0.2397 \pm 0.0010 \pm 0.0008$



$\sin^2\theta_W^{MS}(M_Z)$



hep-ex/0504049 submitted early May

Beyond the Standard Model

(95% confidence level)

* Limit on Λ_{LL} ~ 7 or 16 TeV

* Limit on SO(10) Z' ~ 1 TeV

* Limit on lepton flavor violating coupling ~ $0.01G_F$

Summary

- Progress beyond low energy electroweak theory requires:
  - Exploring the 1 TeV frontier
  - Exploring rare processes at lower energy
- Weak Neutral Current experiments play a central role in testing the electroweak theory
- SLAC E158 is the most sensitive test to date: what can we do next?
- Lower energy implies understanding of atoms, nuclei and nucleons