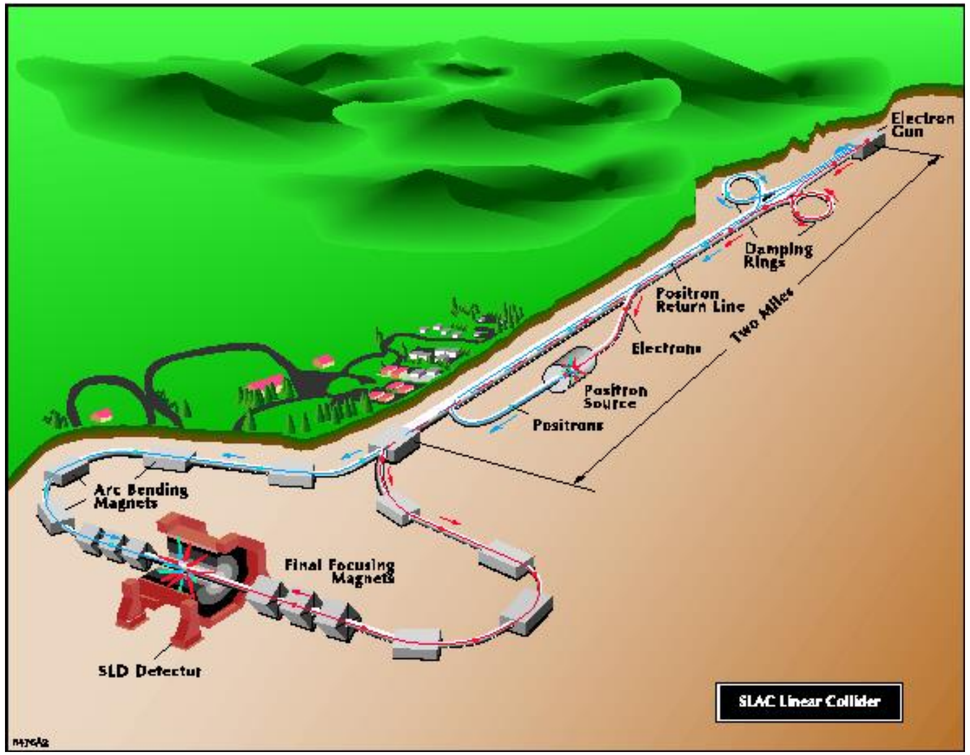
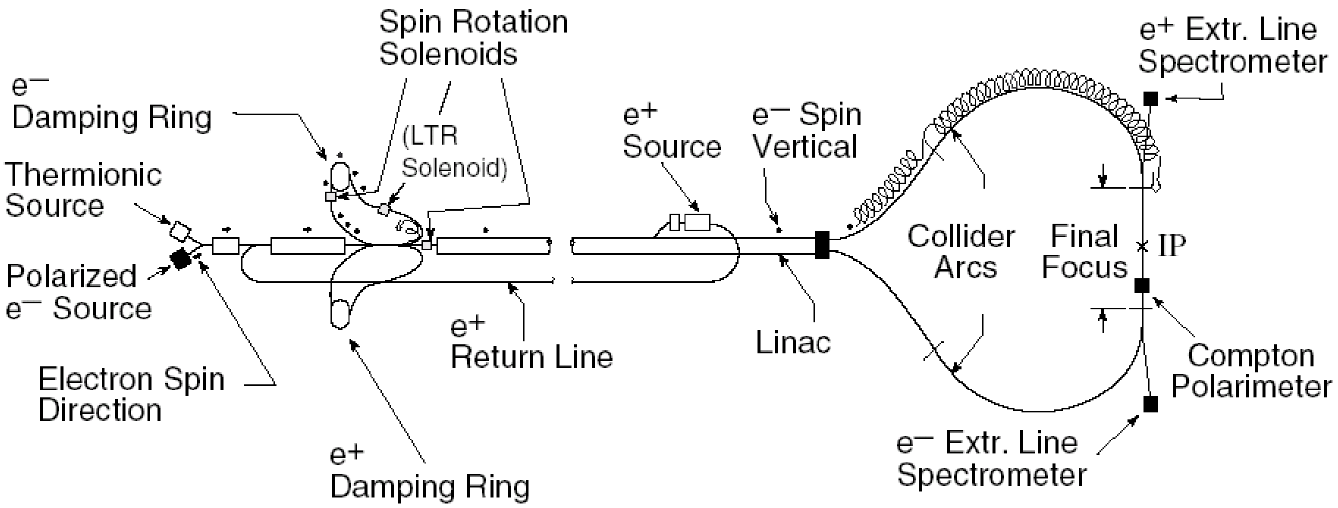
SLD Compton Polarimeter

Mike Woods / SLAC Laser Safety Officer

FCC EPOL Workshop 19-30 September 2022 at CERN

SLD Experiment at the SLAC Linear Collider, 1992 -1998



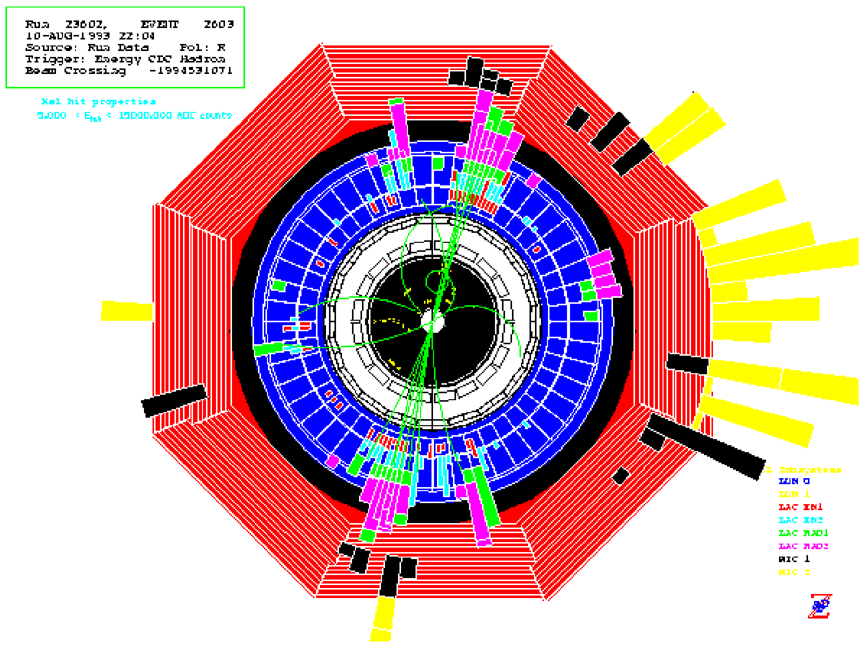


SLAC's Linear Accelerator Facility

LCLS Accelerator (and FACET-II) operate at 120 Hz
LCLS-II Accelerator operates at 1 MHz
First x-ray light from LCLS-II beam to Experimental Halls scheduled for early 2023

A_{LR} Measurement at SLD

$$A_m = \frac{N_L - N_R}{N_L + N_R} = |P_e| A_{LR}$$



Simple Counting Experiment

- can use all final states (no particle ID)
- no kinematic reconstruction
- no need to distinguish fermion from anti-fermion
- no final state interaction effects

Simple Cuts to select hadronic Z events

- Energy imbalance < 0.6
- >22 GeV energy in calorimeter
- 3 or more charged tracks

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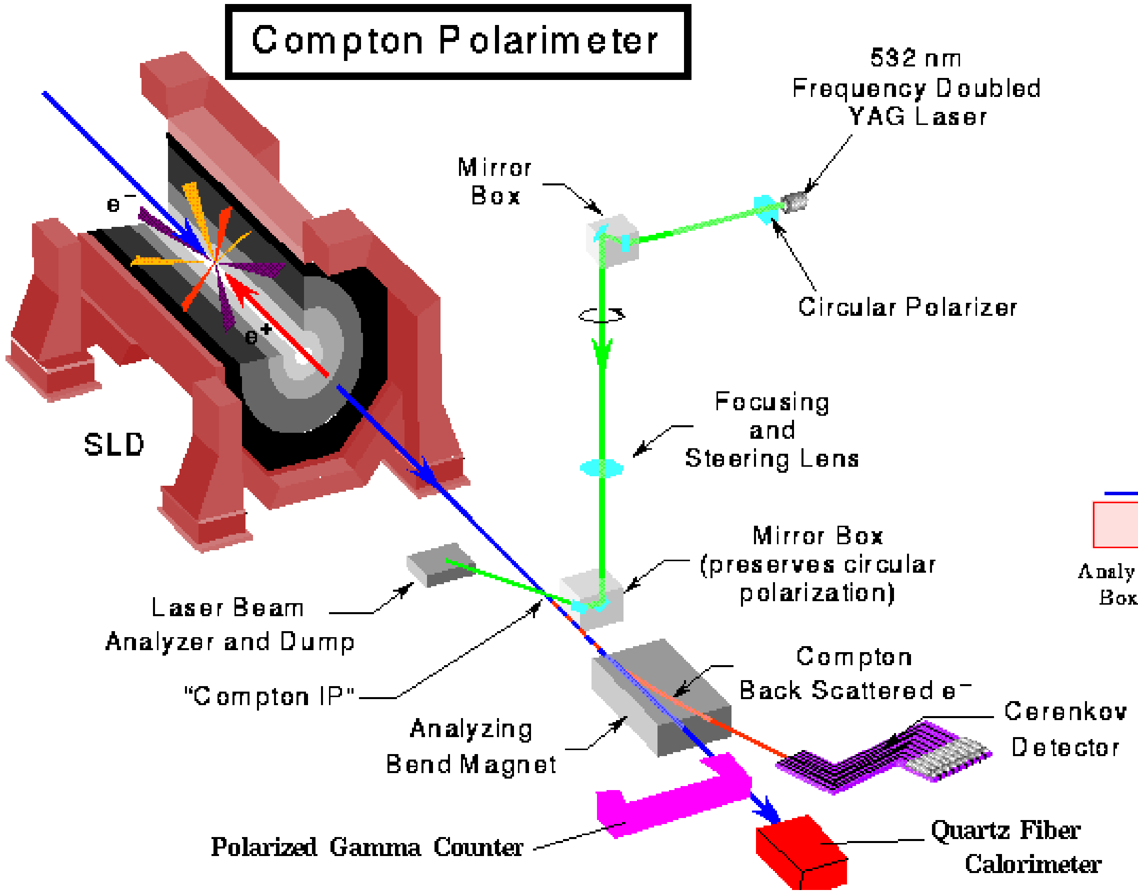
SLD A_{LR} Result and Systematics

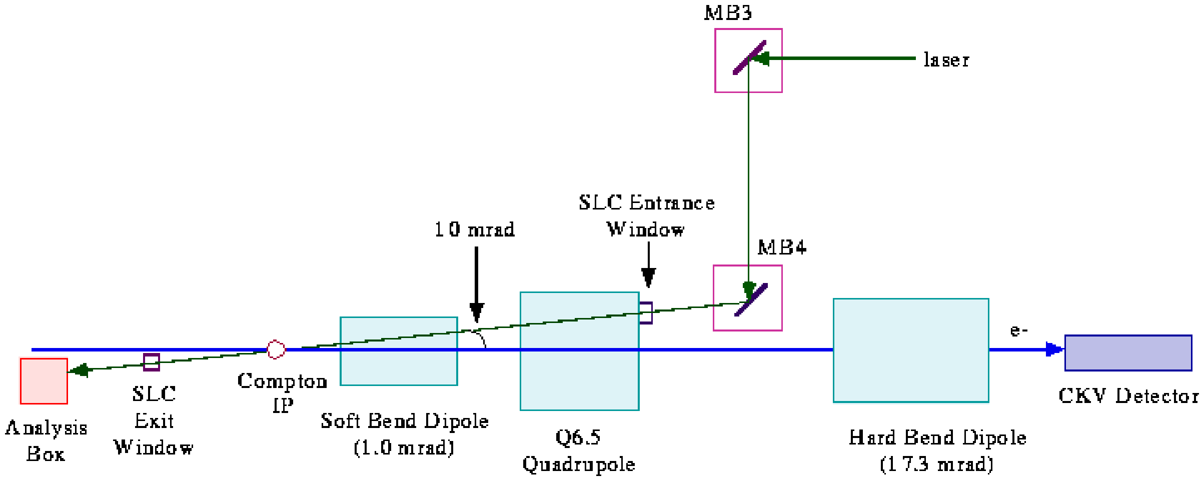
$$A_{LR}^{0} = 0.15138 \pm 0.00216$$
$$\sin^2 \theta_W^{eff} = 0.23097 \pm 0.00027$$

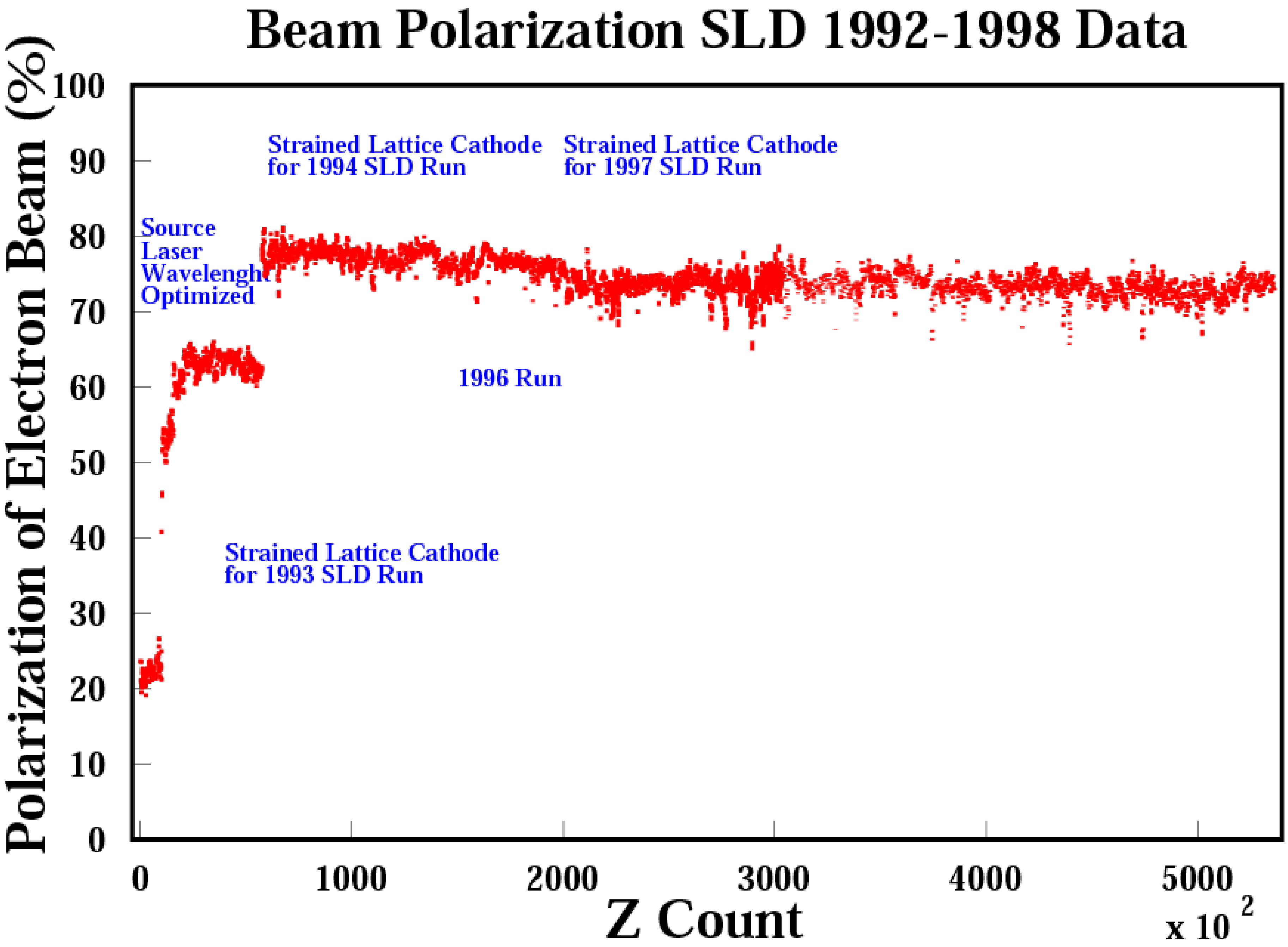
	1992	1993	1994-5	1996	1997-8
Polarimetry	2.7%	1.3%	0.64%	0.50%	0.50%
Energy Scale	-	-	0.33%	0.37%	0.39%
Chromatic Effects	-	1.1%	0.17%	0.16%	0.15%
Bkg., detector,…	2.4%	0.1%	0.06%	0.05%	0.07%
Total Systematic	3.6%	1.7%	0.75%	0.63%	0.64%
Statistics	44%	4.3%	2.8%	3.7%	1.6%

A_{LR} Statistics and Systematic Errors

SLD Compton Polarimeter






Beam Polarization SLD 1992-1998 Data
Polarization of Electron Beam (%)
100
90
80
70
60
50
40
30
20
10
0
Strained Lattice Cathode for 1994 SLD Run
Strained Lattice Cathode for 1997 SLD Run
Source Laser Wavelenght Optimized
1996 Run
Strained Lattice Cathode for 1993 SLD Run
0
1000
2000
3000
4000
5000
Z Count
x 10 2

Features of *SLD* Compton Polarimeter

Physics is well understood QED; radiative corrections <0.1%

- no atomic or nuclear physics corrections (ex. Levchuk effect in Moller polarimetry)
- reference for O(α^3) corrections: M. Swartz, Phys.Rev.D58:014010,1998

Electron beam backgrounds measured with laser off pulses

Polarimetry data taken parasitic to physics data (electron detector only)

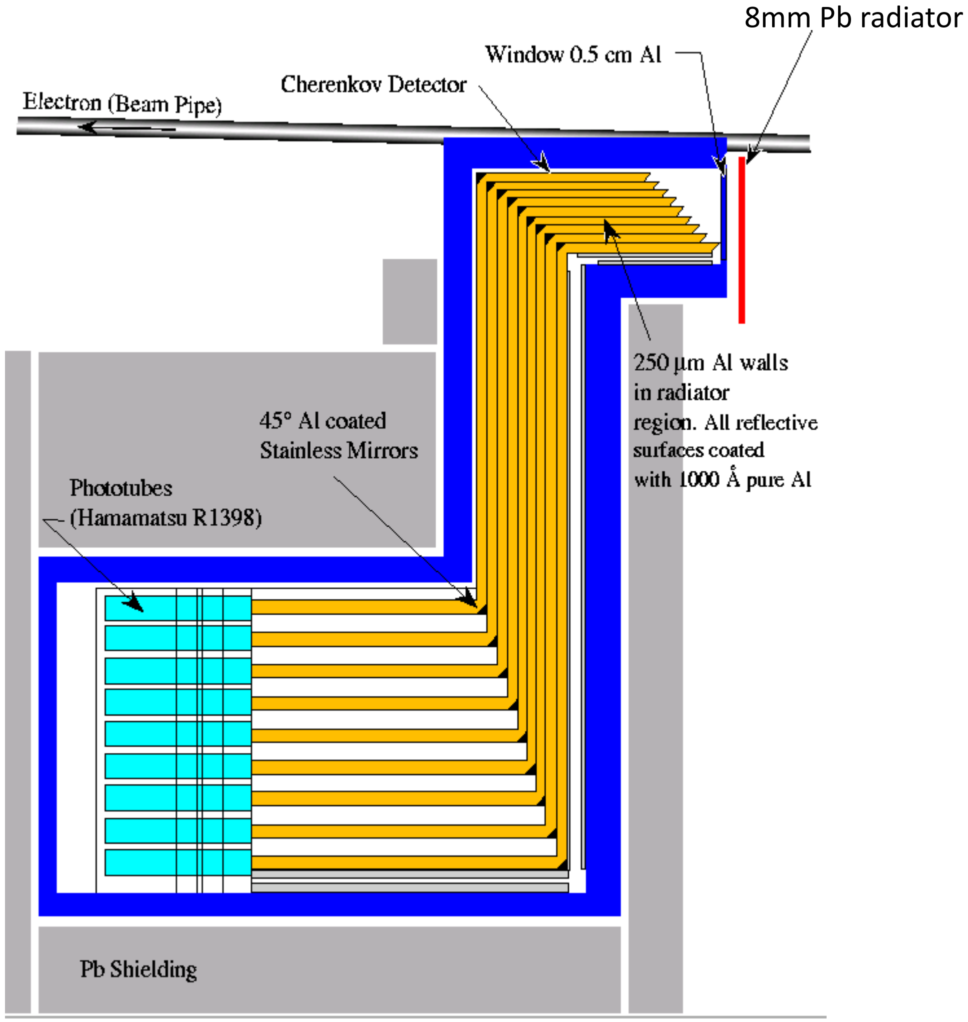
Scattering rate is high; ~1% polarization determination in a few minutes

Laser helicity selected with a pseudo-random sequence

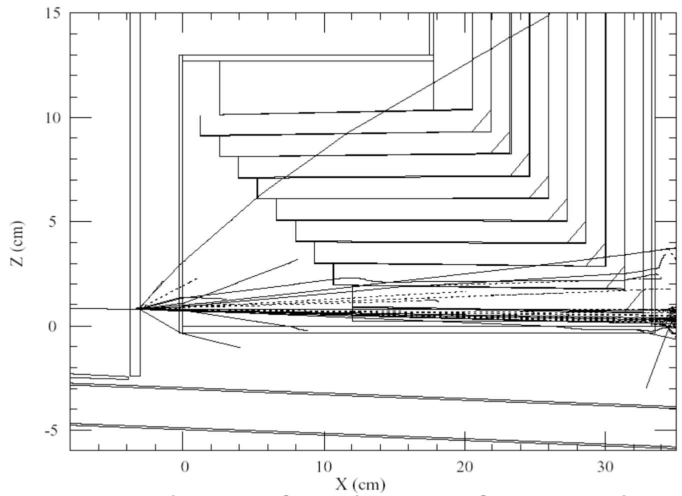
Laser polarization determined to 0.1%

Beam-beam depolarization effects can be measured by comparing measurements with and without collisions

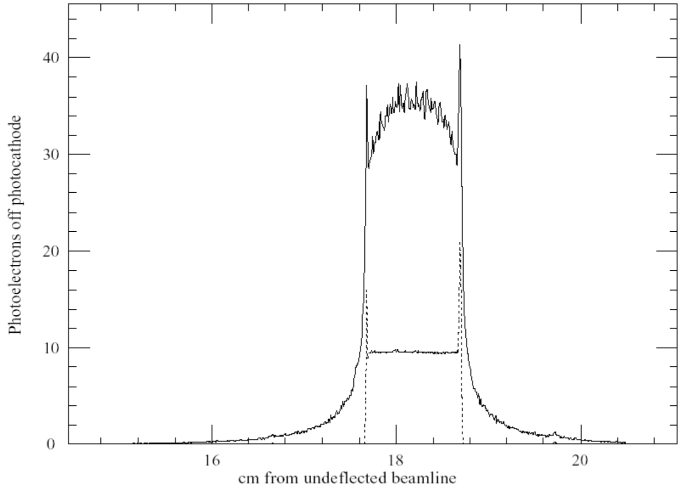
Electron Cherenkov Detector (CKV)



Gas is propane at 1atm; 11 MeV threshold



EGS4 simulation for shower from 1 electron



EGS-generated response function for CKV-7, with (solid line) and without (dashed line) 8mm lead pre-radiator.

Compton Scattering Kinematics

The cross section for Compton scattering is

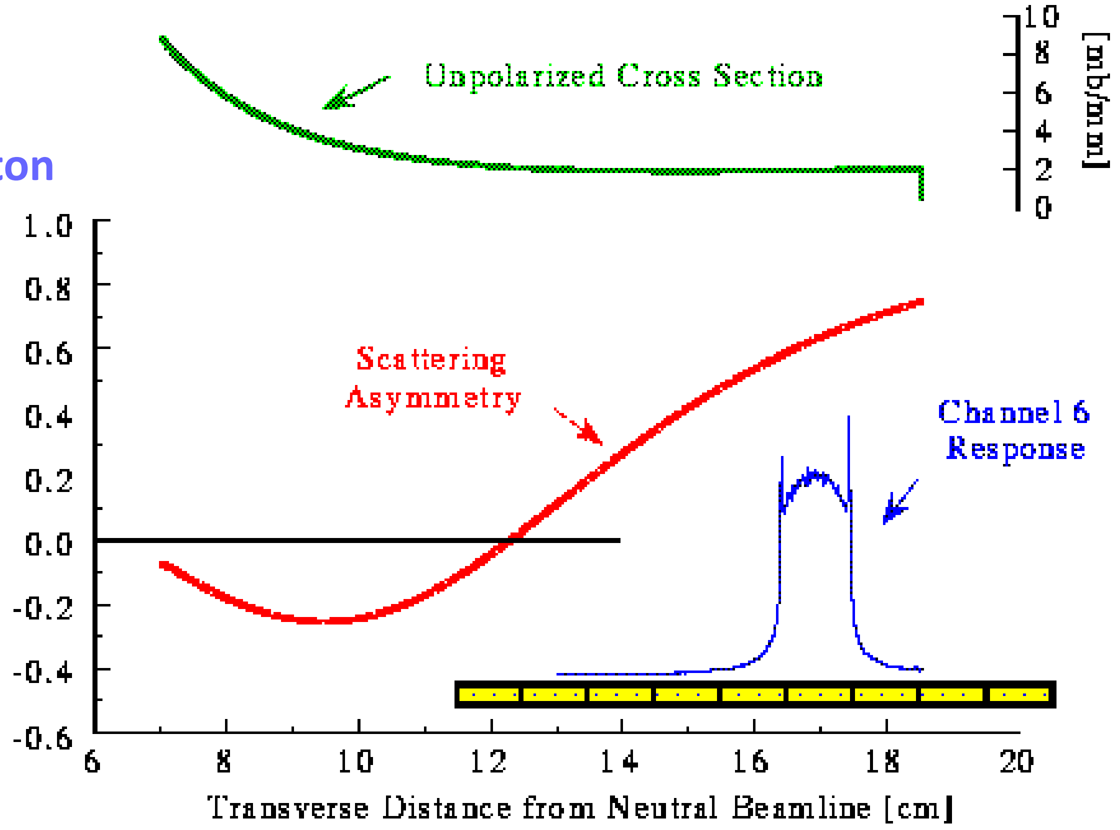
$$\sigma(y) = \sigma_0(y)\left[1 + P_e P_\gamma A(y)\right] \qquad \text{where} \quad y = \frac{E'}{E_0}$$

The measured asymmetry in a channel is

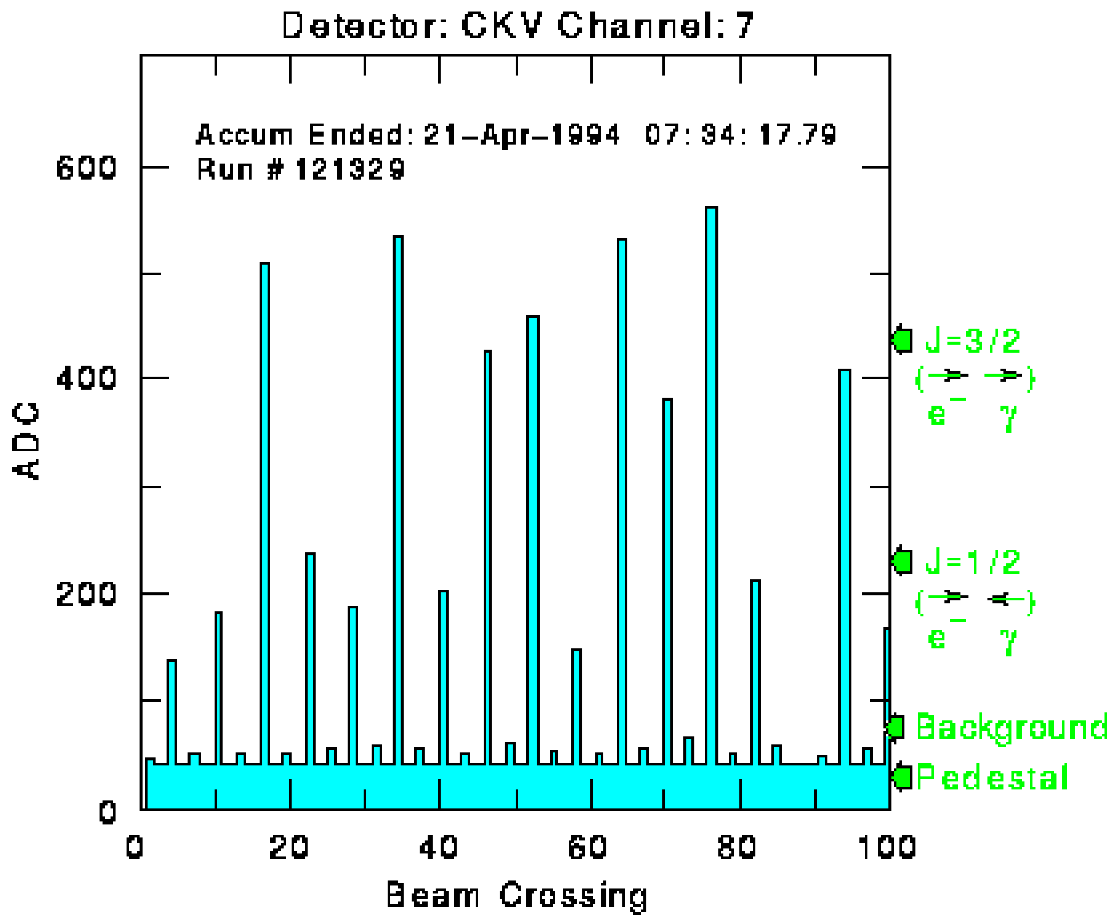
$$A_i^m = \frac{N_i^{\rightarrow\rightarrow} - N_i^{\rightarrow\leftarrow}}{N_i^{\rightarrow\rightarrow} + N_i^{\rightarrow\leftarrow} - 2N_i^{off}} = a_i P_e P_\gamma$$

Where the analyzing power is calculated from the Compton Cross section and the channel response function, R_i.

$$a_i = \frac{\int \frac{d\sigma_0}{dx} A(x) R_i(x)\,dx}{\int \frac{d\sigma_0}{dx} R_i(x)\,dx}$$



Raw Data from CKV Detector (during e- only running)



1994 Commissioning
(P_e ~ 80 %)

7-94
7758A8

Trigger 30 Hz
e^- 10 Hz
$e^-\gamma$ 5 Hz

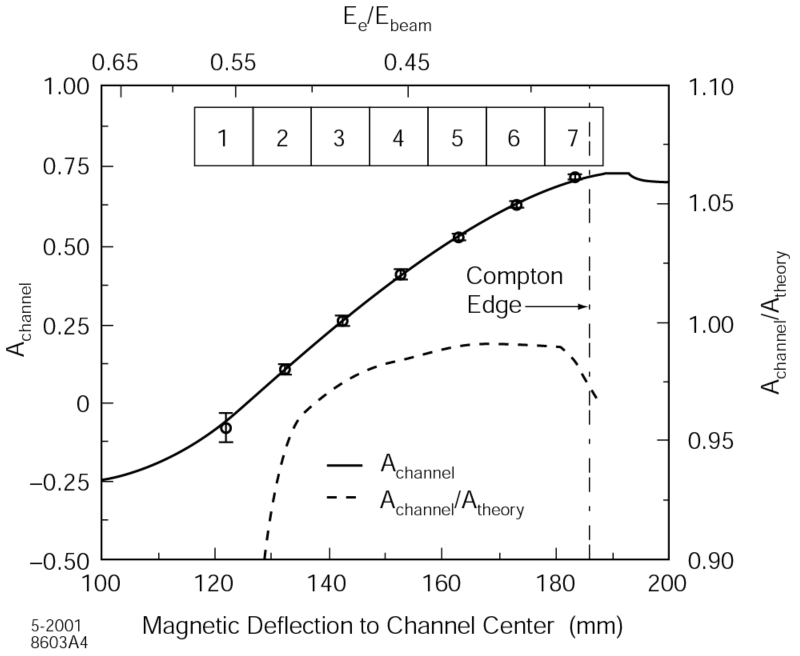
CKV Analyzing Power Determination (Table Scans)

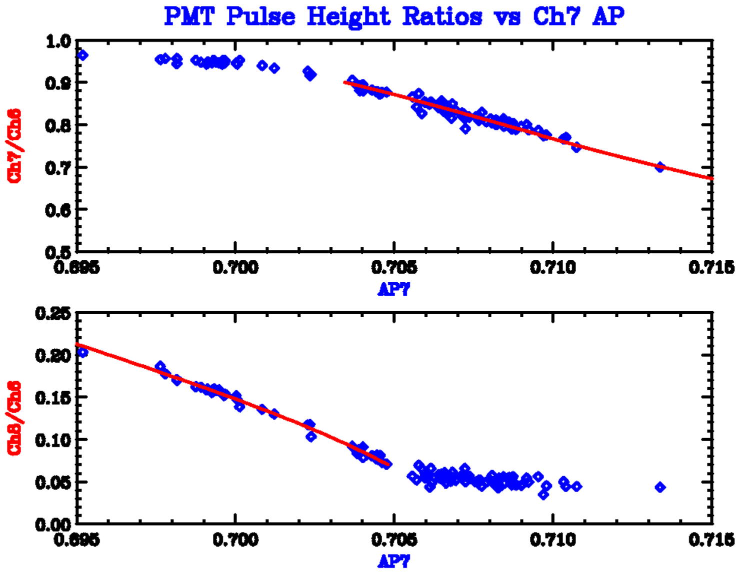
Detector resolution modifies theoretical analyzing power by <2% for CKV7 at Compton Edge

- 11 MeV detector threshold ensures EGS-based simulation is reliable

Table scans sweep detector channels thru Compton Edge

- done daily
- give spectrometer calibration, locate Compton edge, track detector channel gains
- determine CKV7 analyzing power to 0.2%

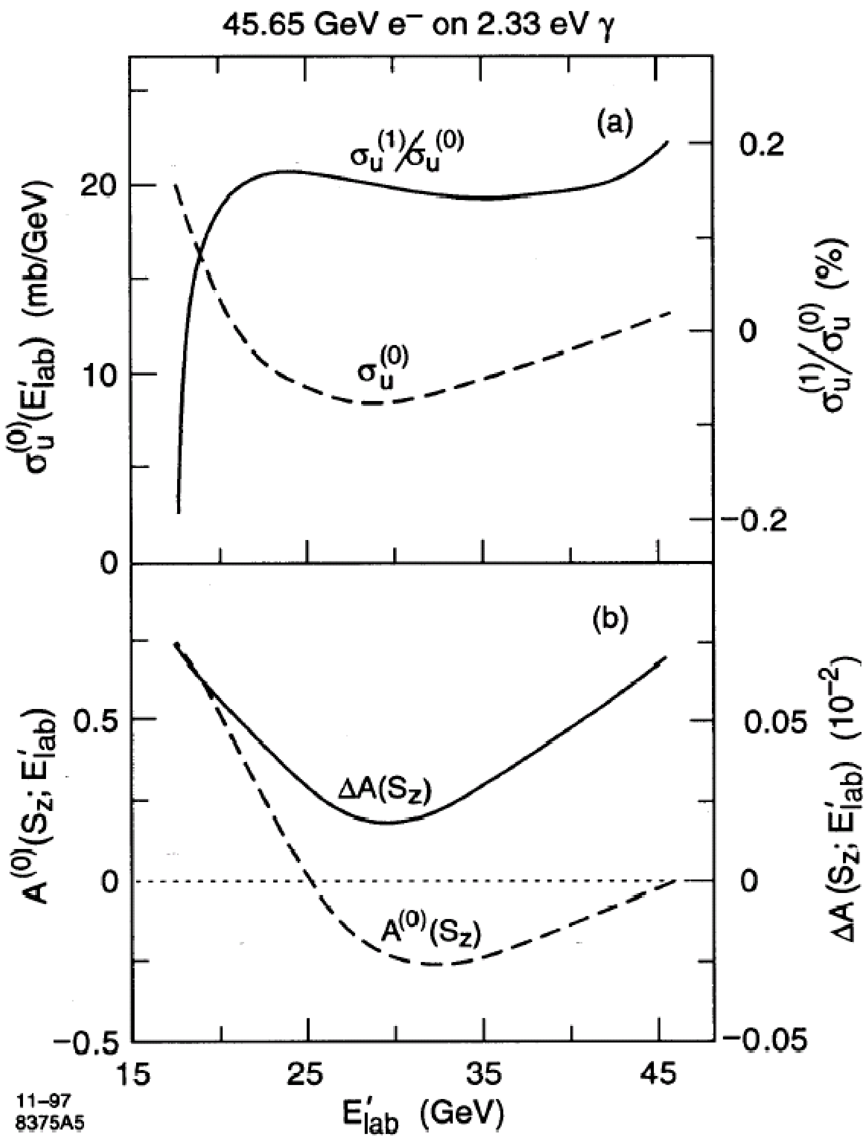




Use pulse height ratios for CKV7/CKV6 and CKV8/CKV6 to track analyzing powers between table scans. Resulting uncertainty in CKV7 AP is 0.3%.

References: SLD Physics Note 50;
E. Torrence Ph.D. thesis, SLAC-Report-509.

Radiative Corrections to Analyzing Powers
1^{st}-order (α^3) corrections

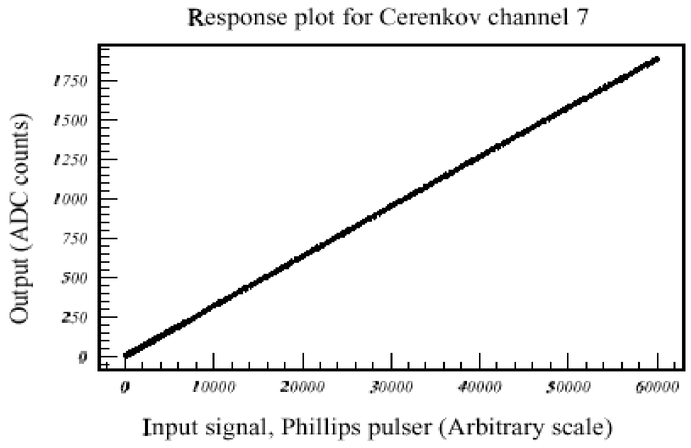


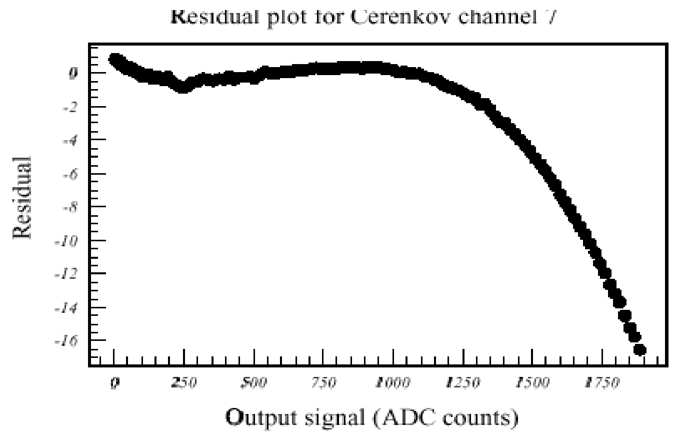
<0.2% corrections to cross section

<0.1% correction to analyzing power at Compton Edge

See M. Swartz, Phys. Rev. **D58**, 014010 (1998)

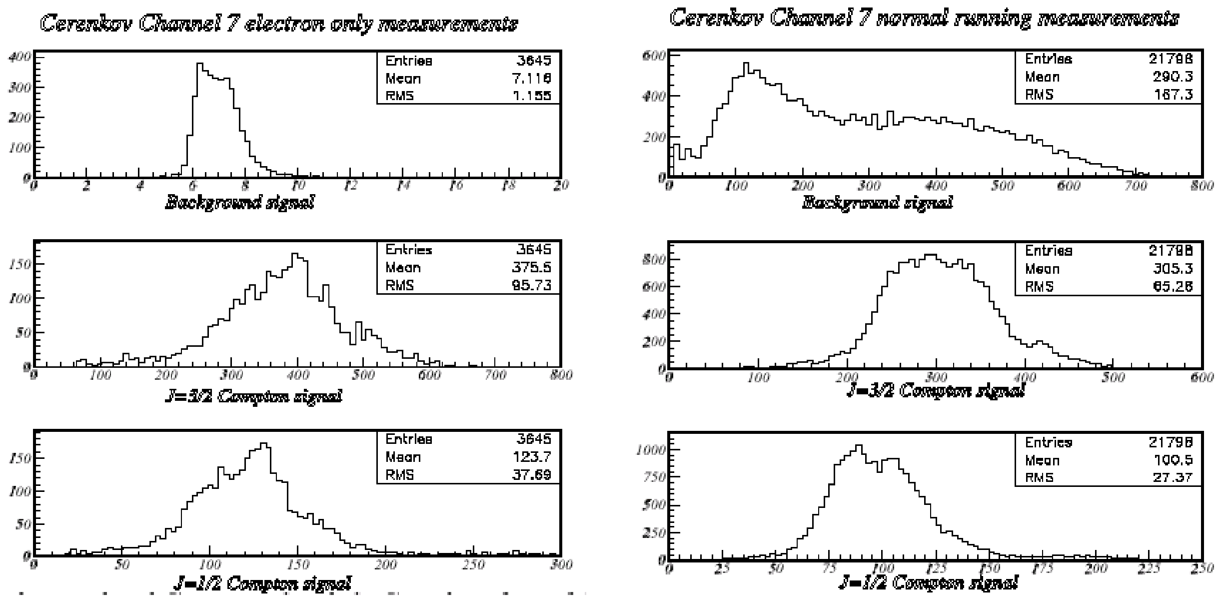
CKV Linearity

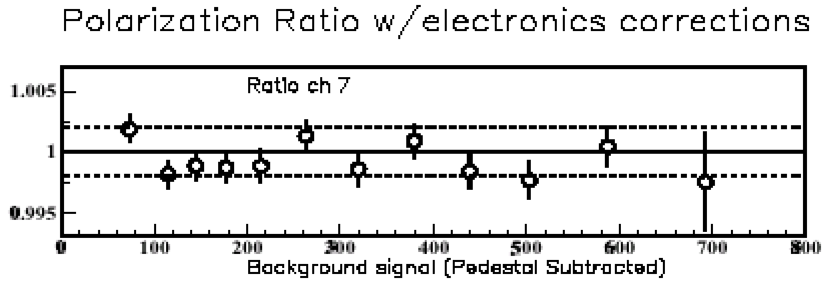




Electronics linearity measured with pulser

Compton asymmetry measured as a function of background level

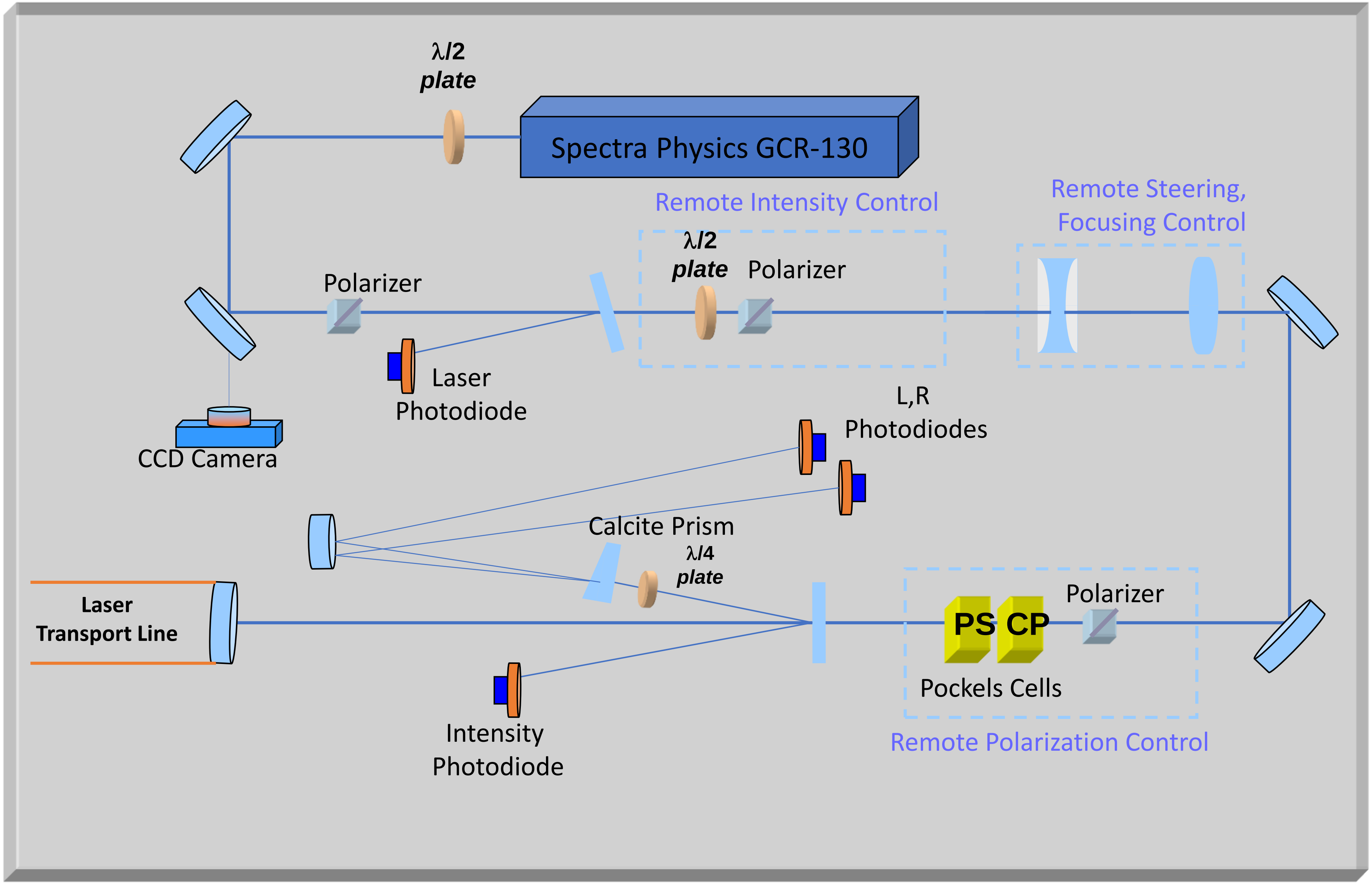


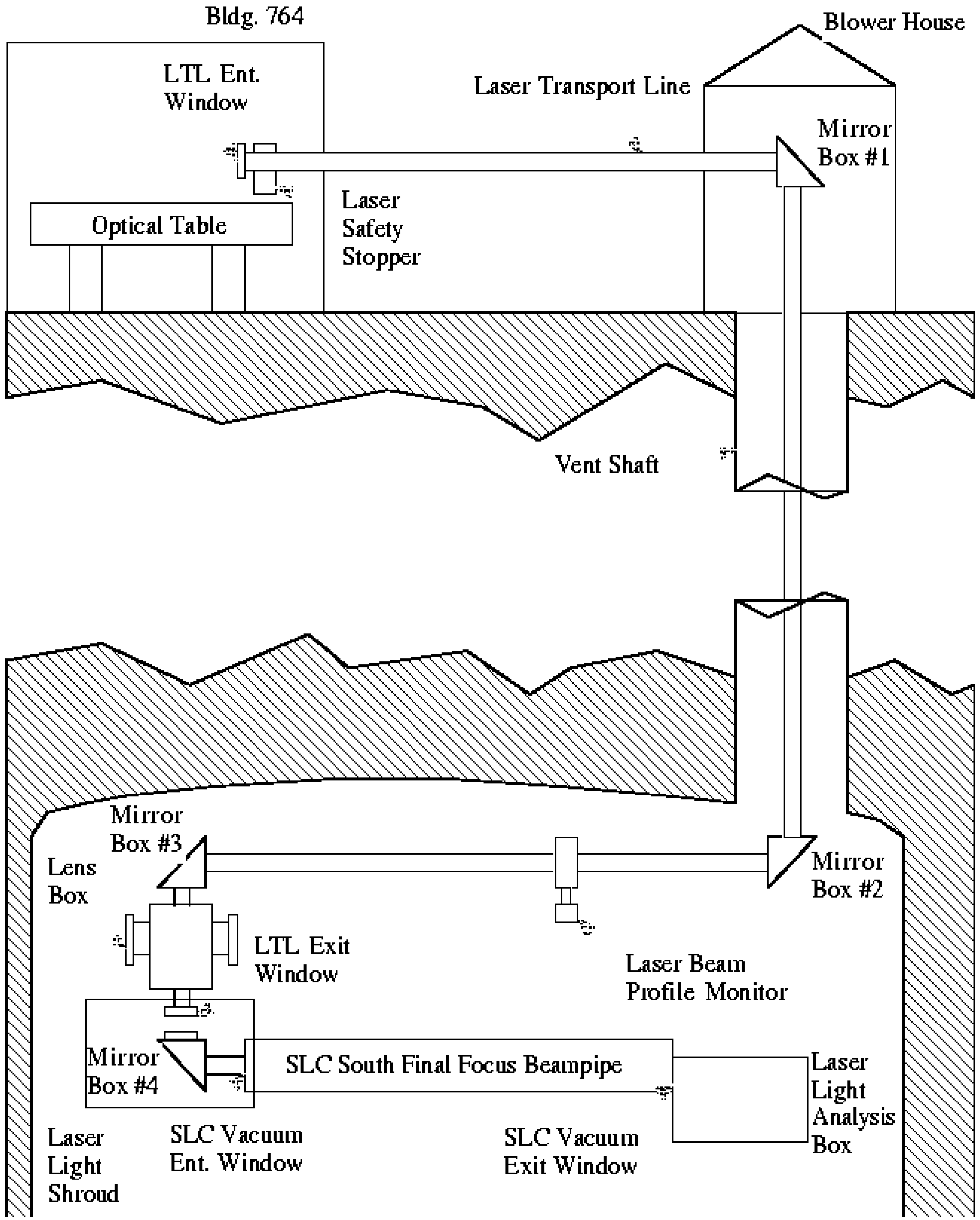


$$\text{Ratio} = \frac{P(\text{collisions})}{P(\text{electron only})}$$

0.2% linearity systematic

Compton Laser System in Laser Room

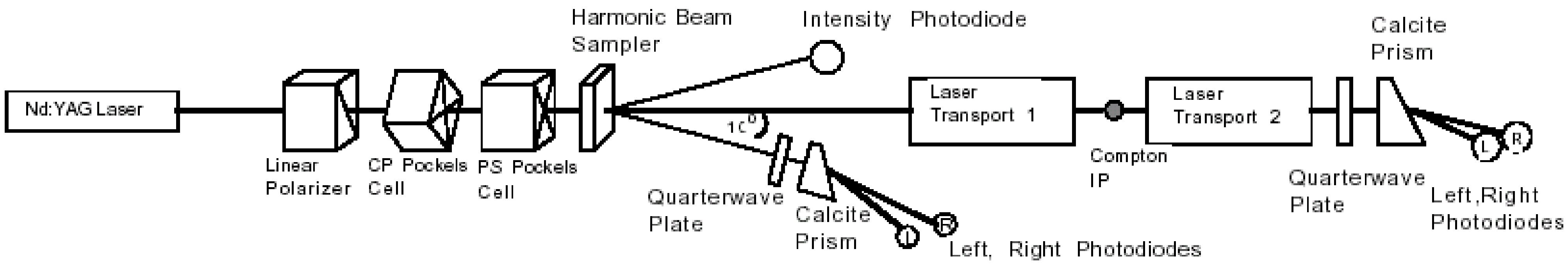


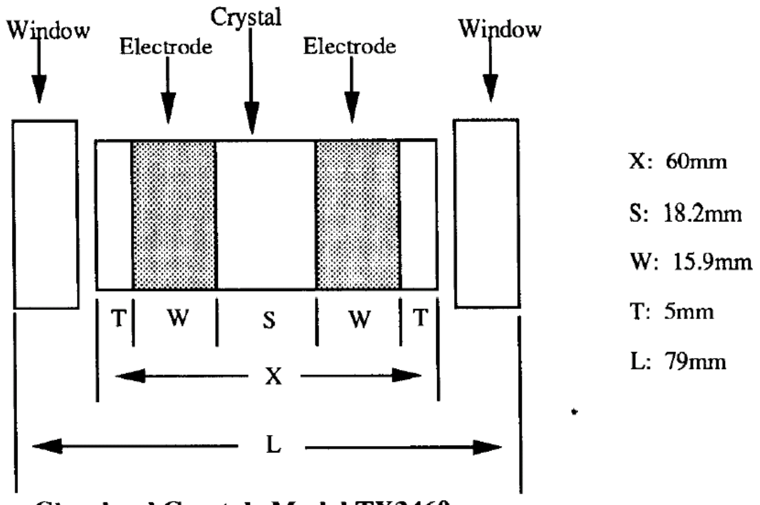


Compton Laser Transport System

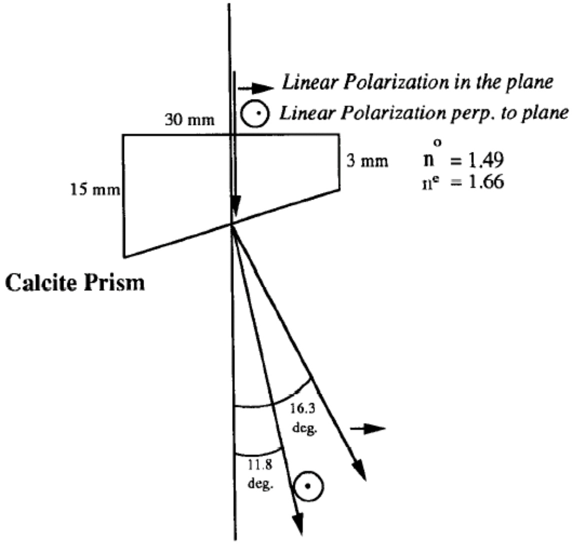
- 40 meters from laser to Compton IP
- Each Mirror Box has 2 helicity-compensating mirrors
- Transport line operates at +3psi nitrogen
- Laser focused to ~0.5mm rms at Compton IP
  (50mJ in 7ns FWHM pulse)

Laser Polarization Control and Analysis





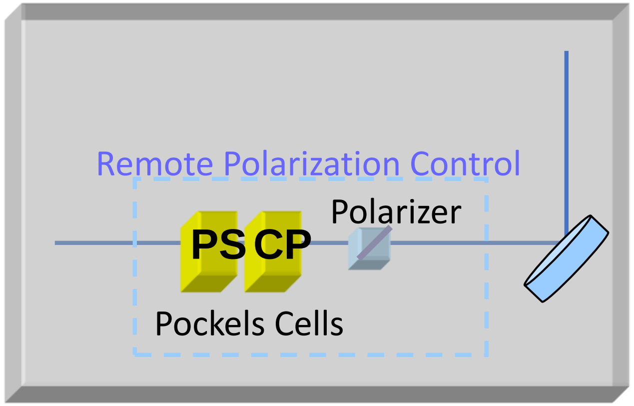
Cleveland Crystals Model TX3460
Pockels Cell



Pockels Cell used for CP, PS

Calcite Prism used in Helicity Filter

Laser Polarization Control



Electric Field Vector after PS Cell in Jones Matrix notation

$$|E\rangle = \begin{bmatrix} \sin\left(\delta_{CP}/2\right) \\ e^{i\left(\pi/2+\delta_{PS}\right)}\cos\left(\delta_{CP}/2\right) \end{bmatrix}$$

Stokes parameters for laser polarization:

$$s_1 = \cos(\delta_{CP}) = \frac{X-Y}{X+Y}$$

$$s_2 = \sin(\delta_{CP})\sin(\delta_{PS}) = \frac{U-V}{U+V}$$

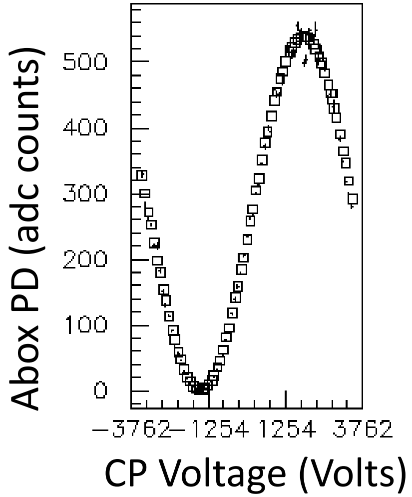
$$s_3 = \sin(\delta_{CP})\cos(\delta_{PS}) = \frac{R-L}{R+L}$$

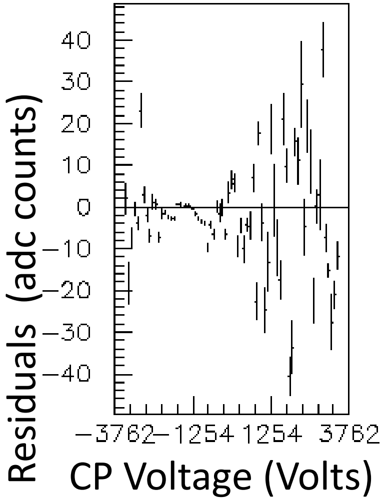
$$\left(s_1^2 + s_2^2\right) + s_3^2 = L^2 + C^2 = 1$$

Allow for imperfect Pockels cells and phase shifts in downstream optics

$$s_3(CIP) = \sin\left(\frac{V_{CP} + \delta V_{CP}^T}{V_{CP}^{\lambda/4}} \cdot \frac{\pi}{2}\right)\cos\left(\frac{V_{PS} + \delta V_{CP}^T}{V_{PS}^{\lambda/4}} \cdot \frac{\pi}{2}\right)$$

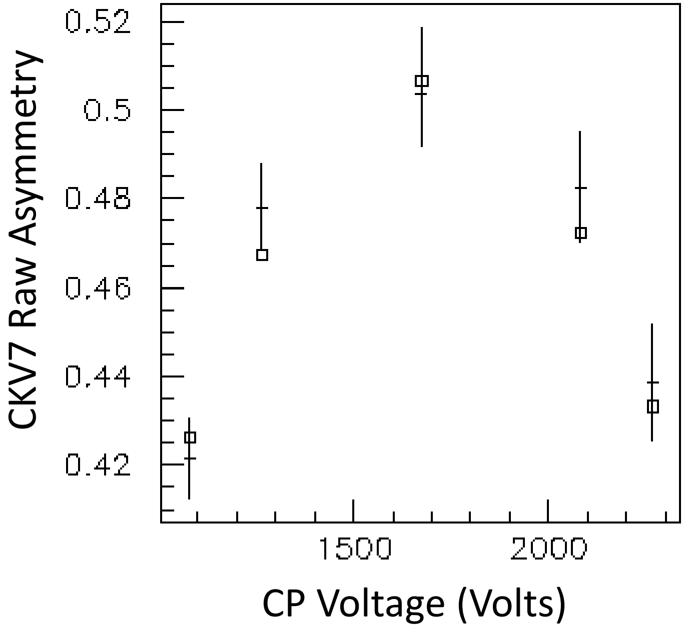
Laser Polarization Scans
and the laser polarization systematic error





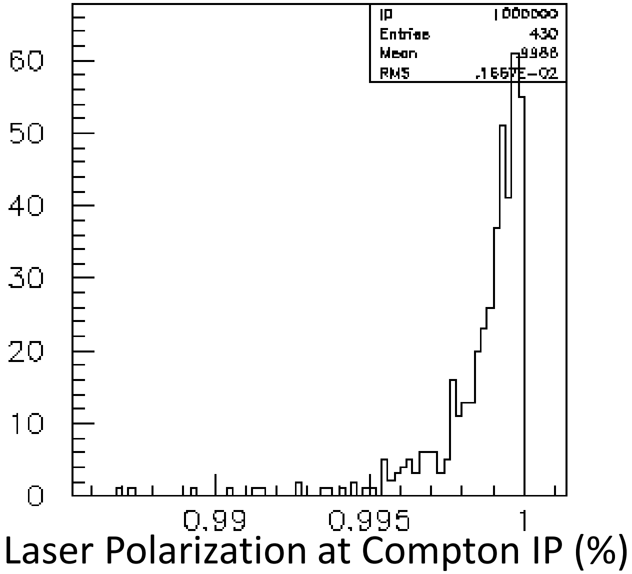
LPSCANS

- done once per hour; readout photodiodes only
- ability to extinguish laser light after Helicity Filter determines polarization purity



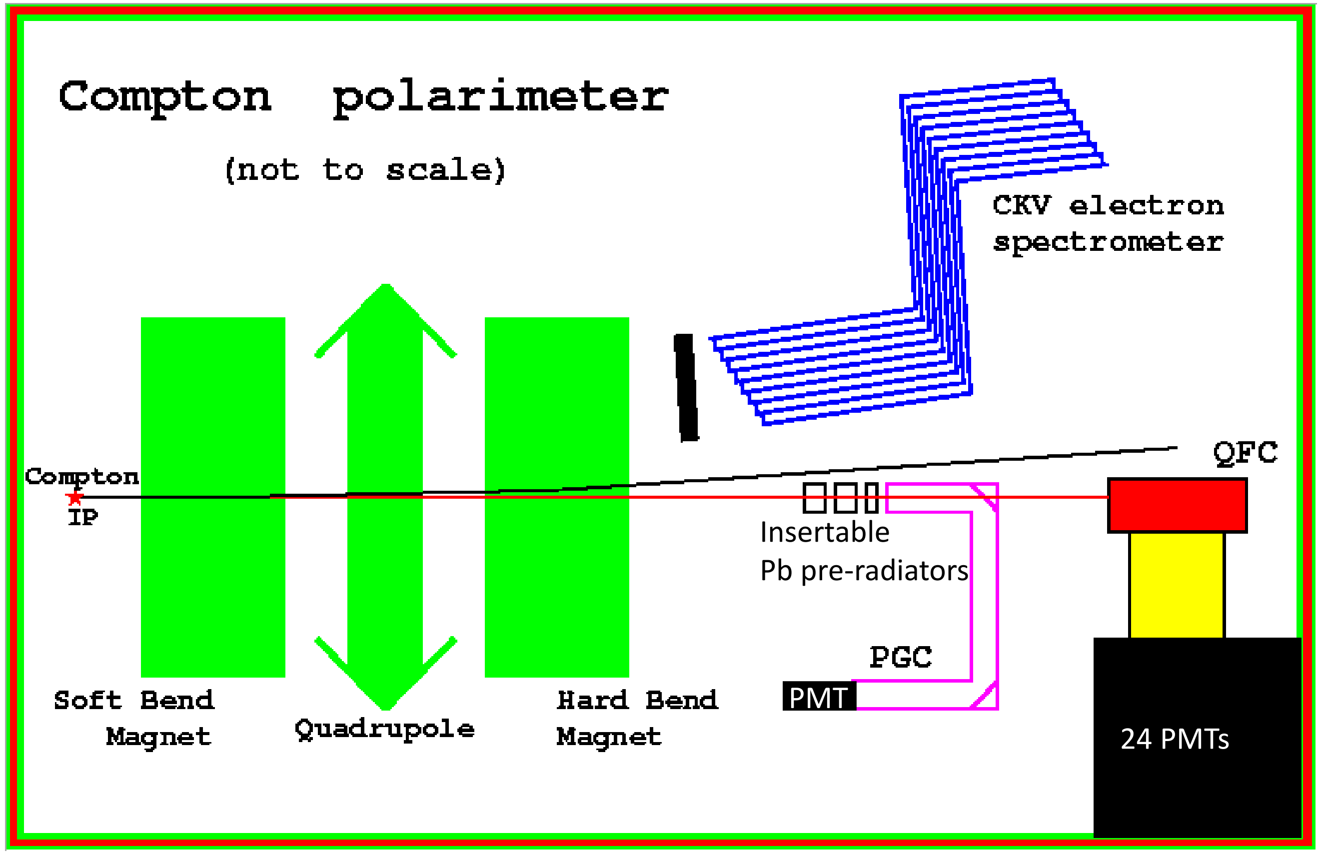
ESCANS

- monitor phase shifts in laser Polarization with continuous Pockels cell scans
- only 1/3 of data is at nominal voltages



→ **0.1% systematic error**

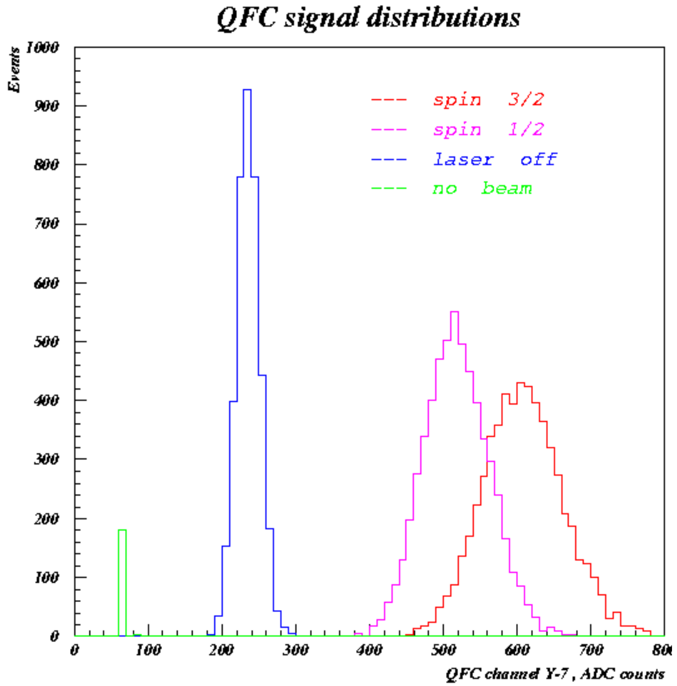
Photon Cross-check Polarimeter Detectors

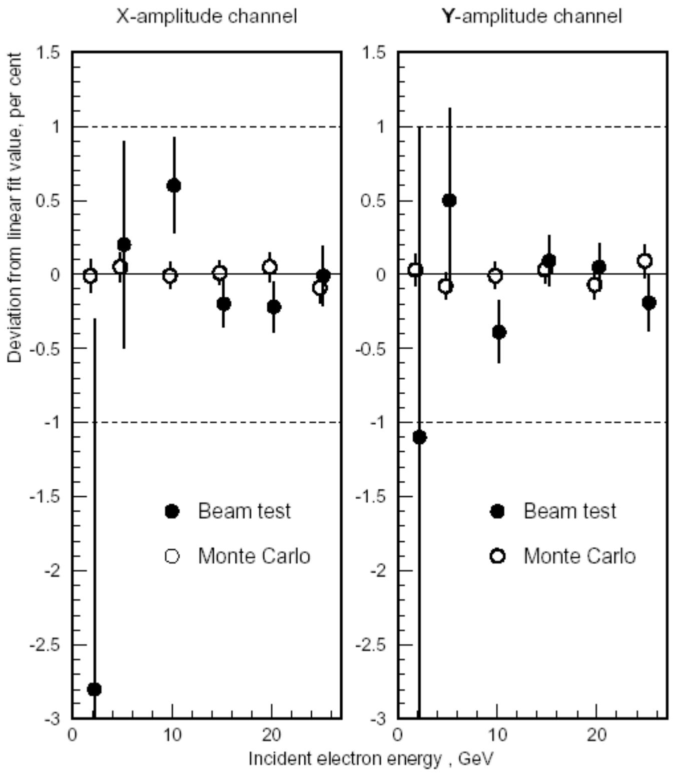


PGC (polarimeter gamma counter) - threshold gas (14 MeV; 1 atm ethylene) Cherenkov counter
- insertable lead pre-radiator; 1 PMT

QFC (quartz fiber calorimeter) - quartz fibers with tungsten radiators; 0.2 MeV threshold
(34 longitudinal sections, each 1 radiation length)
- 24 PMTs (10X, 10Y, SUMX, SUMY, 2 Bkgd)

QFC Data and Systematics

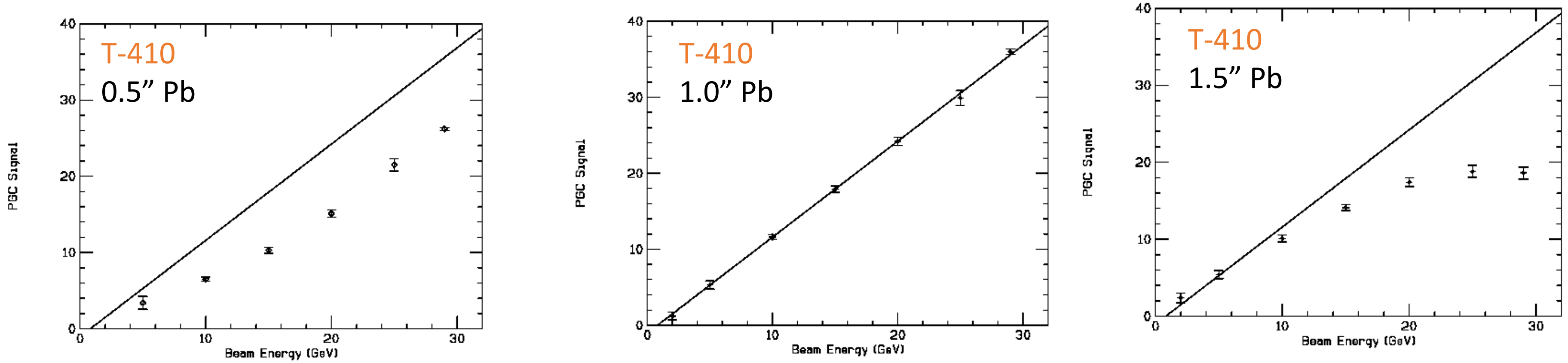


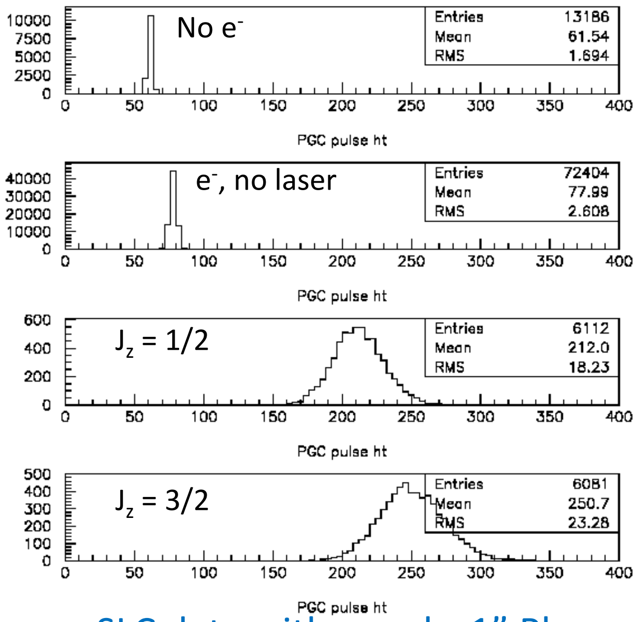


Systematic	Error	Method
Energy Response	0.2%	Beam test, MC
Detector non-uniformity	0.3%	Beam test, MC
Detector mis-alignment	0.1%	Beam test, MC
Angular acceptance, beam size	<0.1%	MC simulation
Optical cross talk	<0.1%	Measurement, MC
Re-scattered electrons	<0.1%	MC, in situ study
Electronics linearity	0.5%	LED study, beam test
Electronics cross-talk	0.1%	In situ study
Laser pickup	0.1%	In situ study
Total	**0.6%**	

D. Onoprienko, SLD-Note-267, 1999
and Ph.D. thesis, SLAC-Report-556, 2000

PGC Data and Systematics





SLC data with e$^-$ only, 1” Pb

Systematic	Error	Method
Energy Response	0.5%	Beam test, MC
Detector effects (uniformity, geometry, linearity)	0.3%	In situ study
Laser pickup	0.1%	In situ study
Total	**0.6%**	

PGC analysis described in R. Frey, SLD-Note-266, 1999 and IEEE Trans. Nucl. Sci. **45**, 670, 1998

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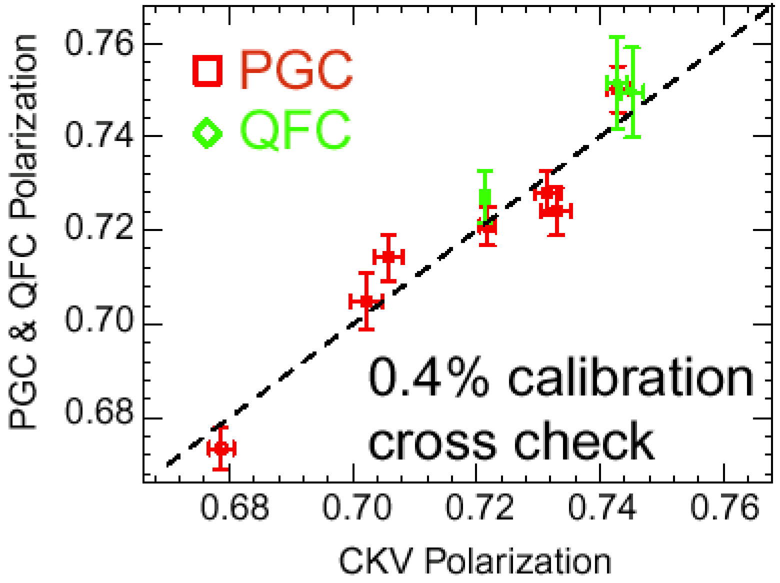
Analyzing Power Systematic Error

CKV7 systematic error in analyzing power estimated at 0.3%
from table scan data that determines location of Compton edge
and accuracy of modeling detector response function

Results from cross-check Polarimeters



Residual of CKV7 polarization to results from PGC and QFC was $\Delta P/P=(0.30\pm0.39)\%$.

0.4% AP systematic error

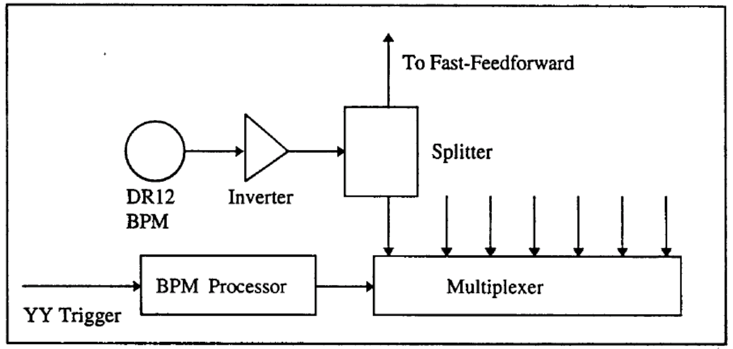
Polarization Summary for all SLD Runs

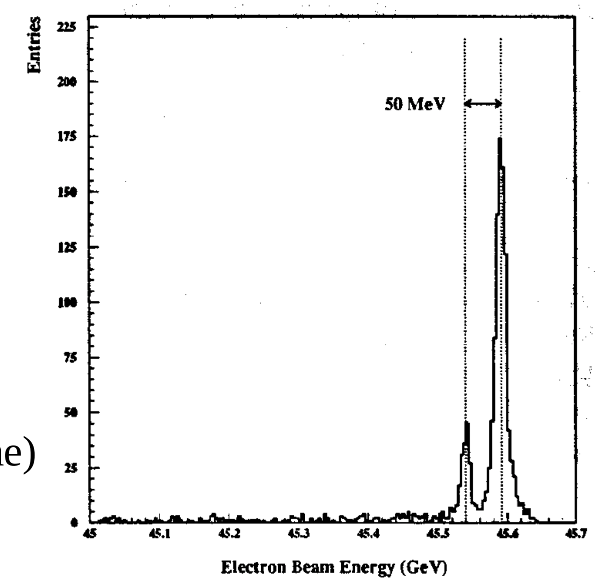
	1992	1993	1994/95	1996	1997/98
Lum-wted Polarization	22.4 ± 0.6 %	63.0 ± 1.1%	77.23 ± 0.52 %	76.16 ± 0.40 %	72.92 ± 0.38 %

Systematic	1992	1993	1994/95	1996	1997/98
Laser Polarization	2.0%	1.0%	0.2%	0.1%	0.1%
Detector Linearity	1.5%	0.6%	0.5%	0.2%	0.2%
Analyzing Power	1.0%	0.6%	0.3%	0.4%	0.4%
Laser Pickup	0.4%	0.2%	0.2%	0.2%	0.2%
Lum-wting Correction	0.2%	1.1%	0.17%	0.16%	0.15%
TOTAL	**2.7%**	**1.7%**	**0.67%**	**0.52%**	**0.52%**

Ph. D. Students: R. Elia, SLAC-Report-429, 1994; R. King, SLAC-Report-452, 1994
A. Lath, SLAC-Report-454, 1994; T. Junk, SLAC-Report-476, 1995
E. Torrence, SLAC-Report-509, 1997; J. Fernandez, SLAC-Report-519, 1999
P. Reinertsen, SLAC-Report-537, 1998; D. Onoprienko, SLAC-Report-556, 2000.

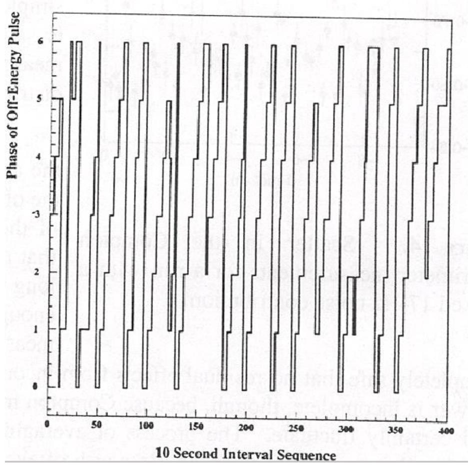
"17 Hz Problem" in the 1994 Run

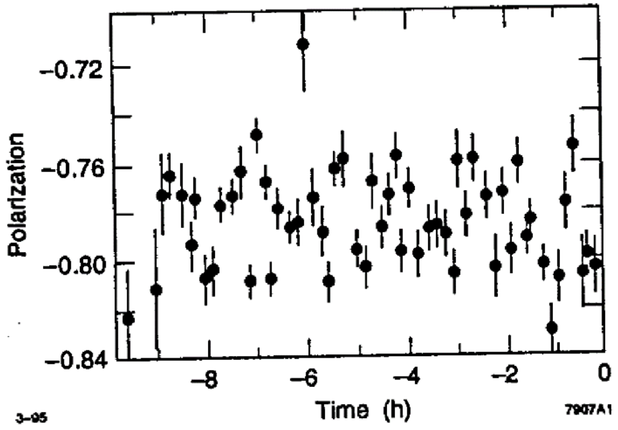




Reflection from inverter (added due to BPM miswiring in downtime) causes every 7th pulse to be off-energy

Observe i) phasing of off-energy pulse wrt laser pulse shifts every 40s
ii) large scatter in electron polarization measurements





Implemented triggering of laser on 6th machine pulse rather than the 7th every ~10 seconds, to ensure beam backgrounds for laser off pulses identical to beam backgrounds for laser on pulses.

Arc Spin Rotation

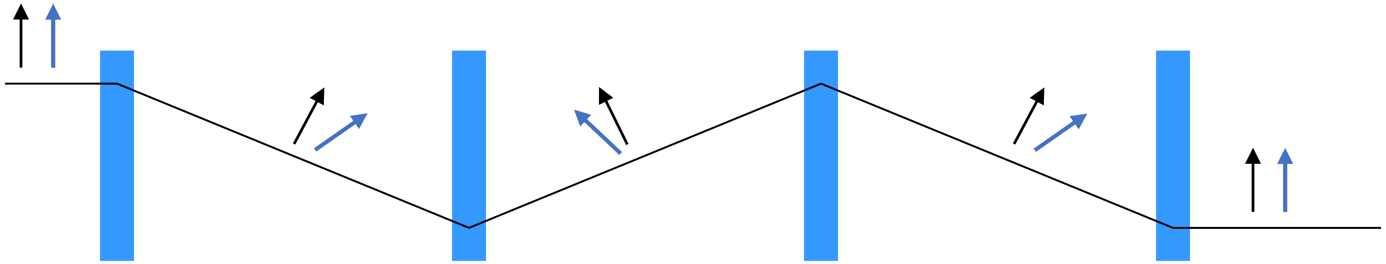
Spin precession in the SLC arc is nearly resonant with vertical betatron oscillation

electron trajectory

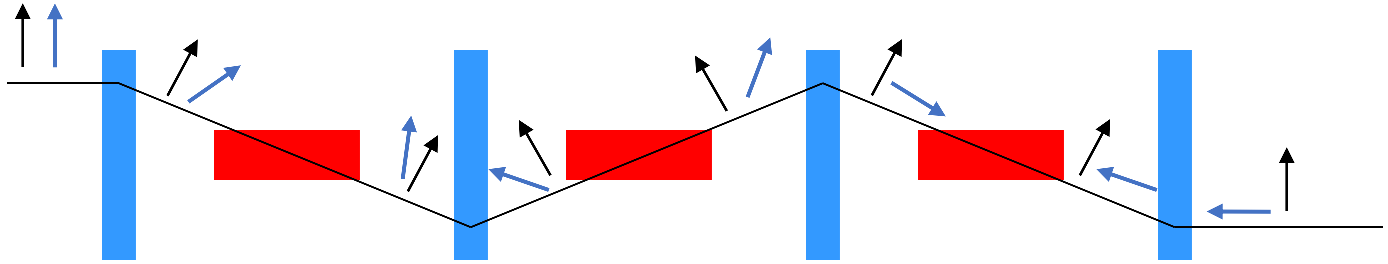
axis perpendicular to trajectory

Spin

1. Vertical betatron oscillation in a quadrupole string



2. Vertical betatron oscillation with horizontal dipoles added



SLC arc consists of 23 achromats.
Each achromat

- **20 combined function magnets**
- **Spin precession of 1085^{0}**
- **Betatron phase advance of 1080^{0}**

SLC arc spin bumps

- **Launch into arc with electron spin vertical**
- **Two orthogonal ‘spin bumps’ allow arbitrary control**
- **Optimize spin bumps to minimize total precession in the arcs reducing polarization dependence on energy**

SLAC

Luminosity-weighted Beam Polarization

$$P_e^{lum-wt} = P_e^{Compton}(1+\xi)$$

1. Chromatic Effect

$$P_e^{lum-wt} = \frac{\int n(E)P(E)L(E)dE}{\int n(E)L(E)dE} \qquad P_e^{Compton} = \frac{\int n(E)P(E)dE}{\int n(E)dE}$$

- determine n(E) from automated wire scans (every 4 hours) at point of high dispersion
  P(E) by varying beam energy (optimize spin bumps to minimize)
  L(E) from optics models and measured dependence of Z production on beam energy

ξ=(+0.12 ± 0.08)% for 1997/98 Run

2. Spin Diffusion
   - incoming beam divergence
   - disruption angles

   ξ=(-0.24 ± 0.08)% correction for 1997/98 run

3. Depolarization due to beamstrahlung spin flip
   - expect effect to be <0.1%
   - effect measured to be <0.001 by comparing polarization measurements with and without positrons present

   ξ=(0.0 ± 0.1)%

Summary

- 0.5% precision achieved
- CKV table scans + laser Pockels Cell voltage scans for optimization, calibration + determining systematics
- many systematic checks performed (e.g. with QFC and PGC detectors)
- enabled SLD's precise parity violation measurements
- data taken parasitic to physics data
- some dedicated beam time needed for systematics studies
- polarimeter measures average beam polarization, so need to address luminosity-weighted polarization
- many details are in references given, including 8 Ph.D. theses