Compton Polarimetry at Jefferson Lab

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Jefferson Lab

Intersections Between Nuclear Physics and Quantum Information

March 28-30, 2018

1. Compton scattering for electron beam polarimetry
2. Compton polarimetry at Jefferson Lab
   → Techniques and apparatus
   → Precision
   → Application for nuclear physics experiments

Polarized Electrons at Jefferson Lab

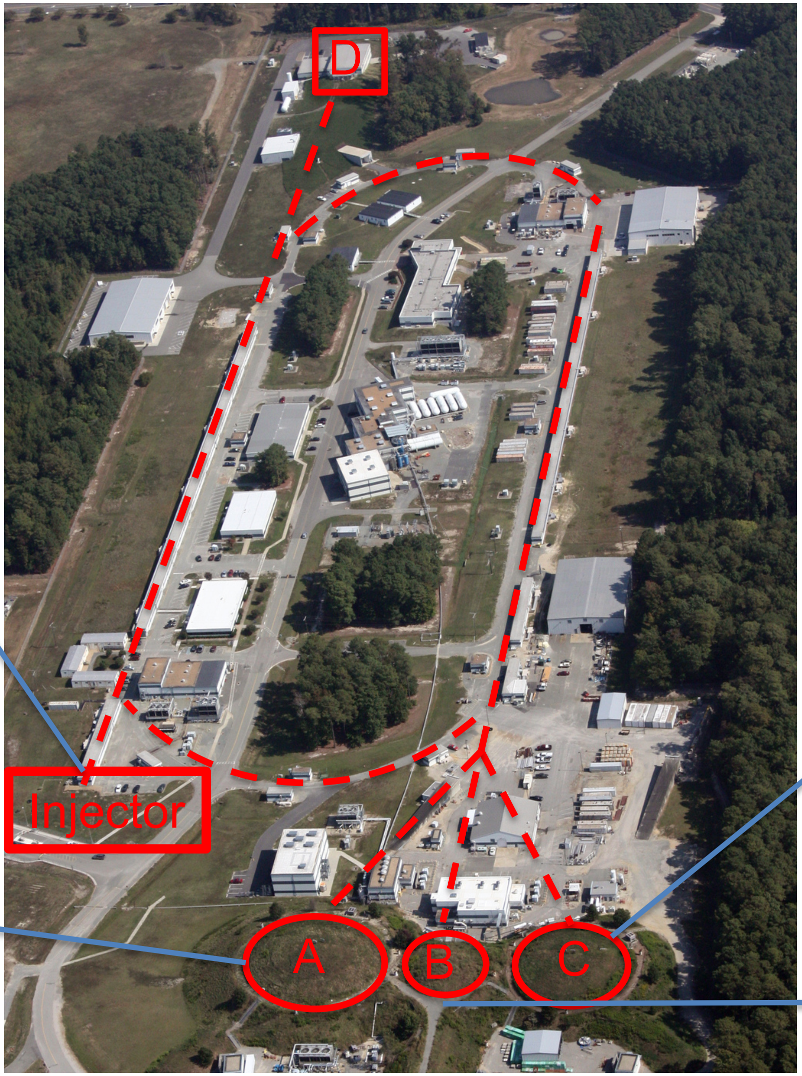
- Polarized electron beam at JLab has enabled a large program of measurements aimed at understanding hadronic structure
  - Proton elastic form factors via recoil proton polarization
  - Double-spin asymmetries with polarized proton, deuteron and ^{3}He targets → polarized quark PDFs
  - Parity violating electron scattering to probe strange quarks in nucleon
- Most experiments of the above type require only modest precision in knowledge of beam polarization (dP/P~2-3%)
- More recently, PVES experiments have been used to probe for new physics beyond the Standard Model – for such experiments, beam polarization becomes one of the limiting systematics
  - Q-Weak (elastic ep) → dP/P < 1%
  - MOLLER (elastic ee) → dP/P < 0.5%
  - SOLID (PVDIS) → dP/P ~0.4%

Future

JLab Accelerator and Polarimeters

E_{beam}=1-12 GeV
I_{beam} ~ 100 μA

P=85-90%



Injector
5 MeV Mott Polarimeter

Hall A
Compton Polarimeter
- IR → Green laser

Møller Polarimeter
- In plane, low field target → out of plane saturated iron foil

Hall C
Compton Polarimeter
- Installed 2010 (Q-Weak)

Møller Polarimeter
- Out of plane saturated iron foil

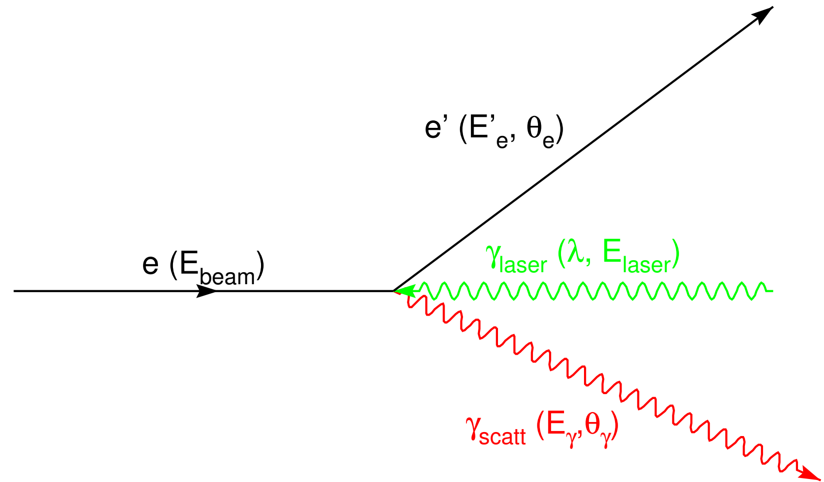
Hall B
Møller Polarimeter
- In plane, low field target

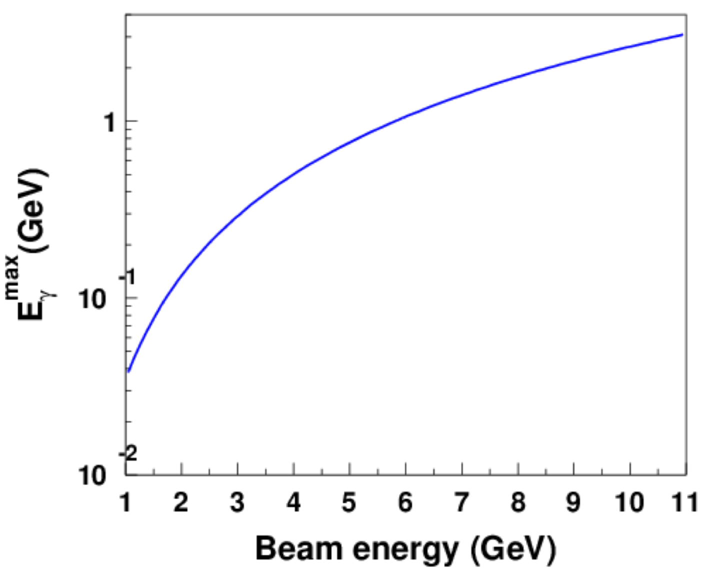
Compton Scattering - Kinematics

Laser beam colliding with electron beam nearly head-on

$$E_\gamma \approx E_{\text{laser}} \frac{4a\gamma^2}{1 + a\theta_\gamma^2\gamma^2}$$

$$a = \frac{1}{1 + 4\gamma E_{\text{laser}}/m_e}$$





Maximum backscattered photon energy at θ=0 degrees (180 degree scattering)

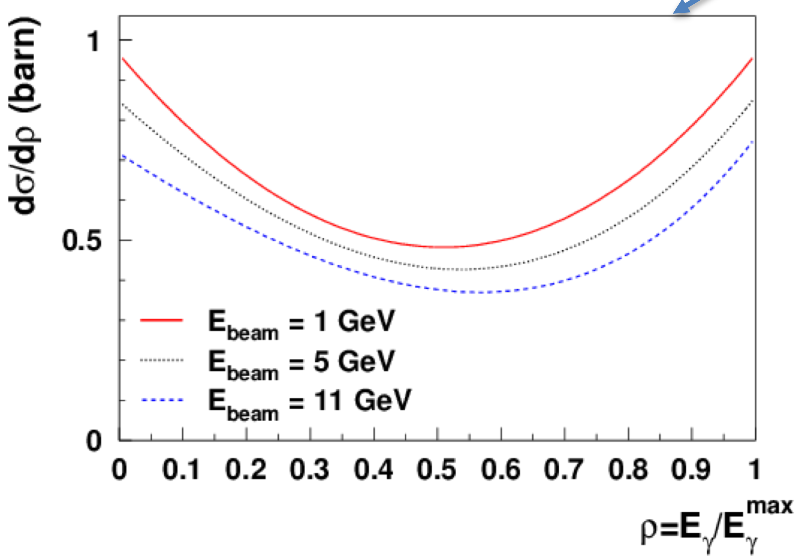
<u>For green laser (532 nm):</u>

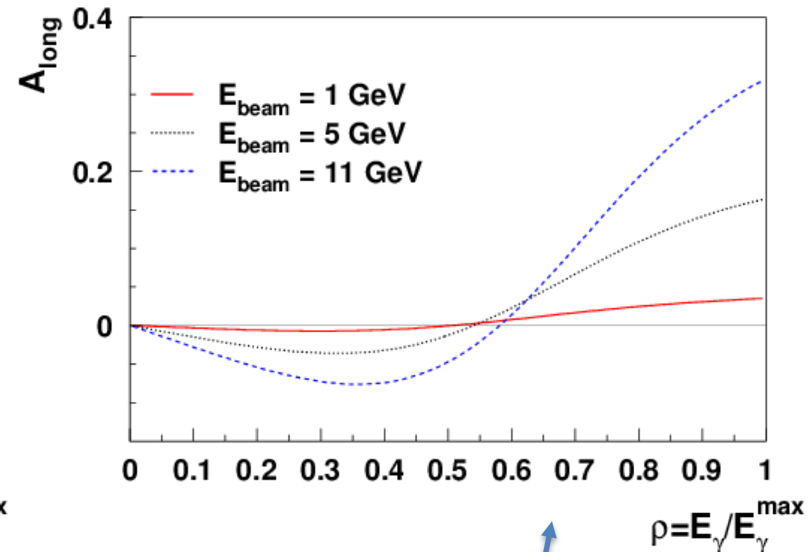
→ E_γ^{max} ~ 34.5 MeV at E_{beam}=1 GeV
→ E_γ^{max} = 3.1 GeV at E_{beam}=11 GeV

Compton Scattering – Cross Section and Asymmetry

$$\rho = \frac{E_\gamma}{E_\gamma^{\max}}$$

$$\frac{d\sigma}{d\rho} = 2\pi r_o^2 a \left[\frac{\rho^2(1-a)^2}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right]$$





$$A_{\text{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} (1-\rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^2} \right]$$

Compton Polarimetry at JLab

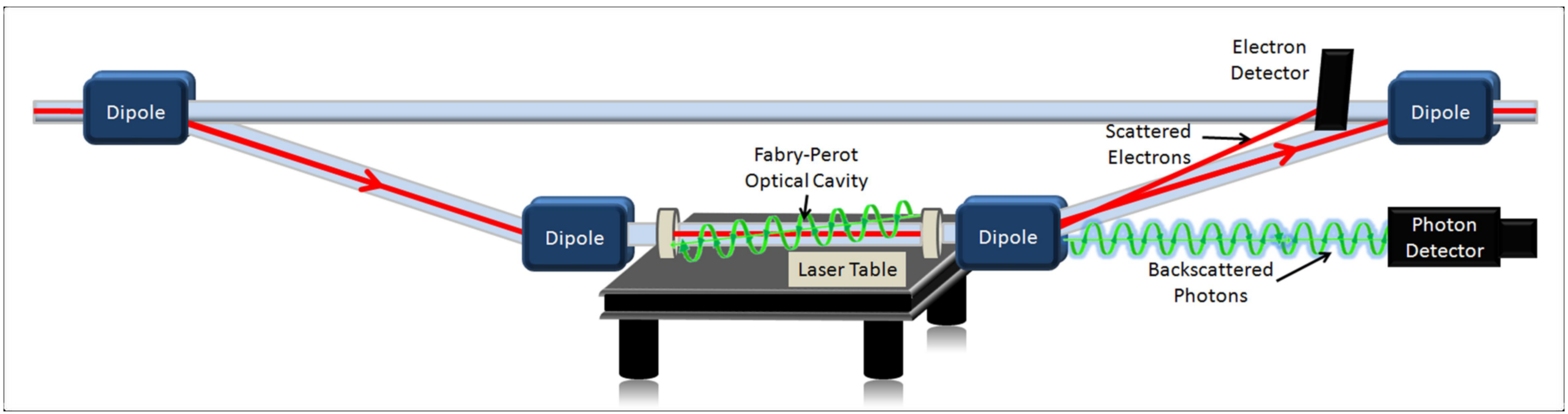
- Compton polarimetry routinely used at colliders/storage rings before use at JLab
- Several challenges for use at JLab
  - Low beam currents (~100 μA) compared to colliders
    - Measurements can take on the order of hours
    - Makes systematic studies difficult
  - At lower energies, relatively small asymmetries
    - Smaller asymmetries lead to harder-to-control systematics
- Strong dependence of asymmetry on E_γ leads to non-trivial determination of analyzing power
  - Understanding the detector response crucial

JLab Compton Polarimeters

Hall A and C have similar (although not identical) Compton polarimeters

Components:

1. 4-dipole chicane: Deflect electron beam vertically
   - 6 GeV configuration: Hall A → 30 cm, Hall C → 57 cm
   - 12 GeV configuration: Hall A → 21.5 cm, Hall C → 13 cm
2. Laser system: Fabry-Pérot cavity pumped by CW laser resulting in few kW of stored laser power
3. Photon detector: PbWO4 or GSO – operated in integrating mode
4. Electron detector: segmented strip detector



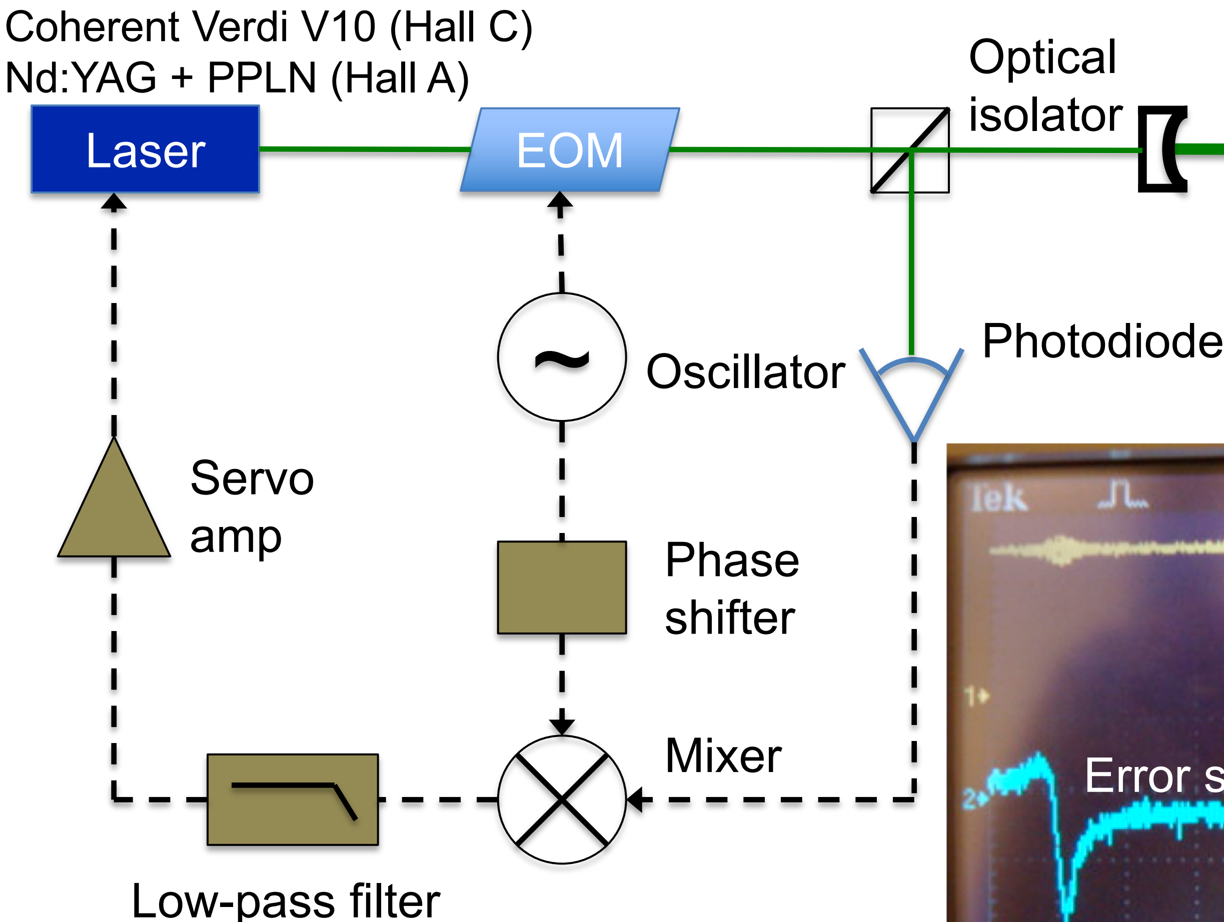
Fabry-Pérot Cavity

- Compton polarimeter measurement time a challenge at JLab
  - Example: At 1 GeV and 180 μA, a 1% (statistics) measurement with 10 W CW laser would take on the order of 1 day!
  - Not much to be gained with pulsed lasers given JLab beam structure (nearly CW)

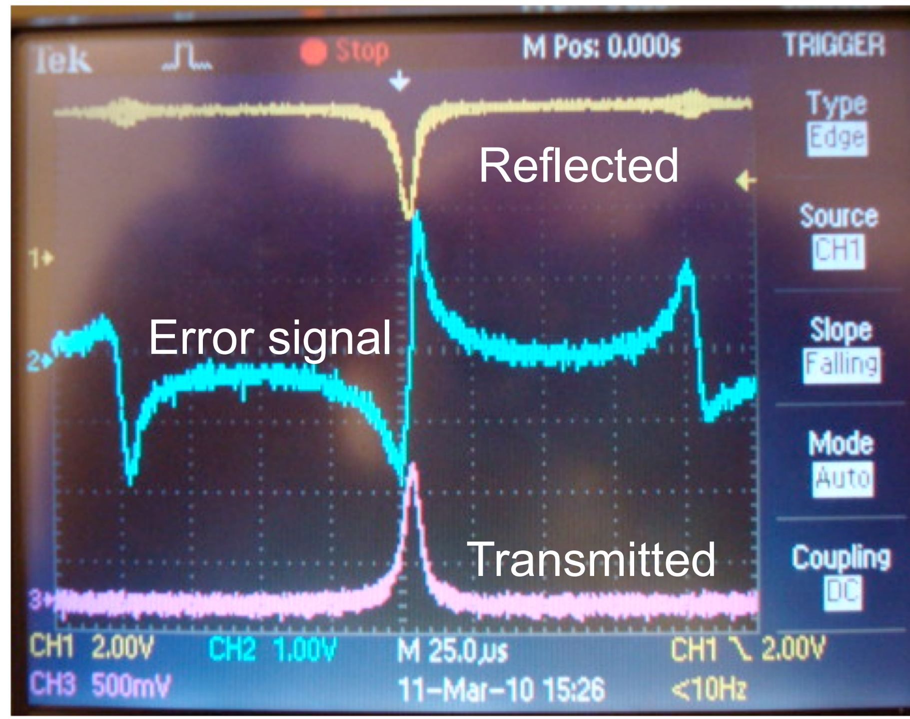
- A high-finesse (high-gain) Fabry-Pérot cavity locked to narrow linewidth laser is capable of storing several kW of CW laser power
  - First proposed for use at JLab in mid-90's, implemented in Hall A in late 90's (Hall C in 2010, HERA..)

- Requires routing electron beam through center of cavity
  - Radiation damage to mirrors an early concern
  - Need non-zero crossing angle between laser and beam → some reduction in FOM

Fabry-Pérot Cavity

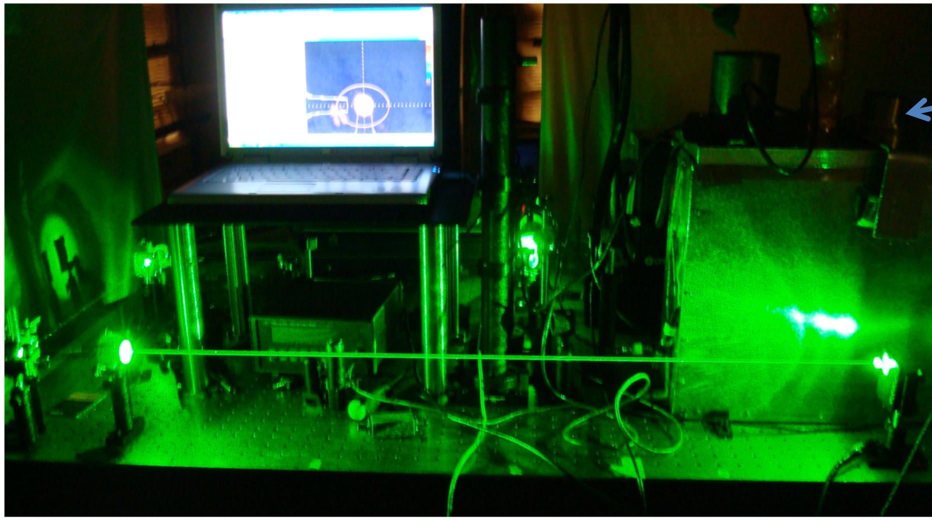


Stored power:
1-2 kW (Hall C)
2-10 kW (Hall A)

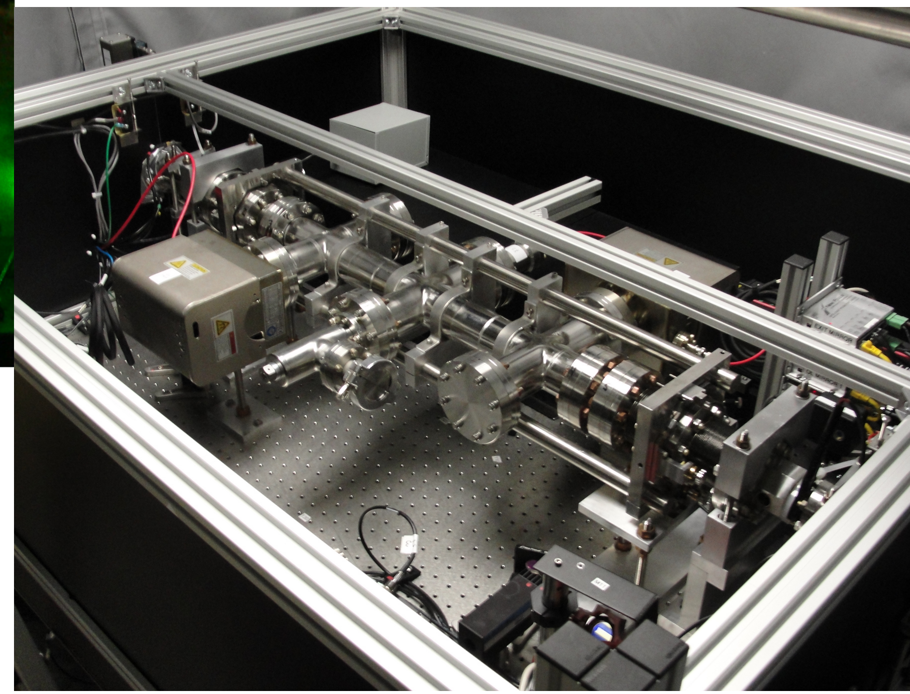


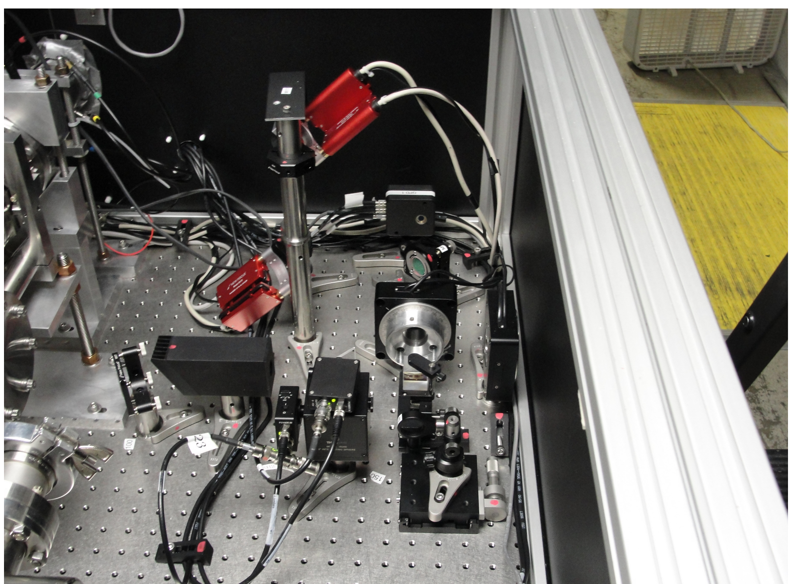
CW laser (1 or 10 W) @ 532 nm locked to low gain, external Fabry-Pérot cavity via Pound-Drever-Hall technique

Fabry-Perot Cavity



Locked cavity from development tests at UVa

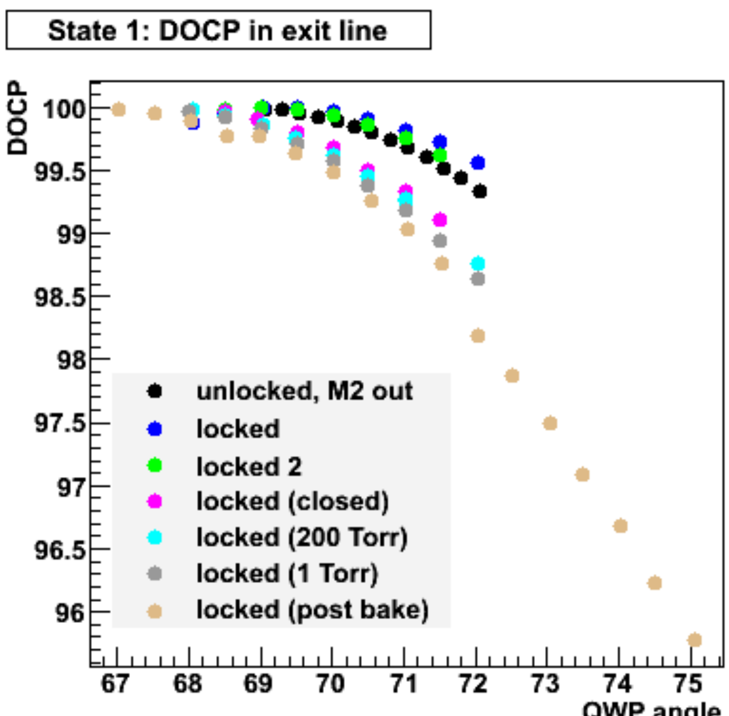


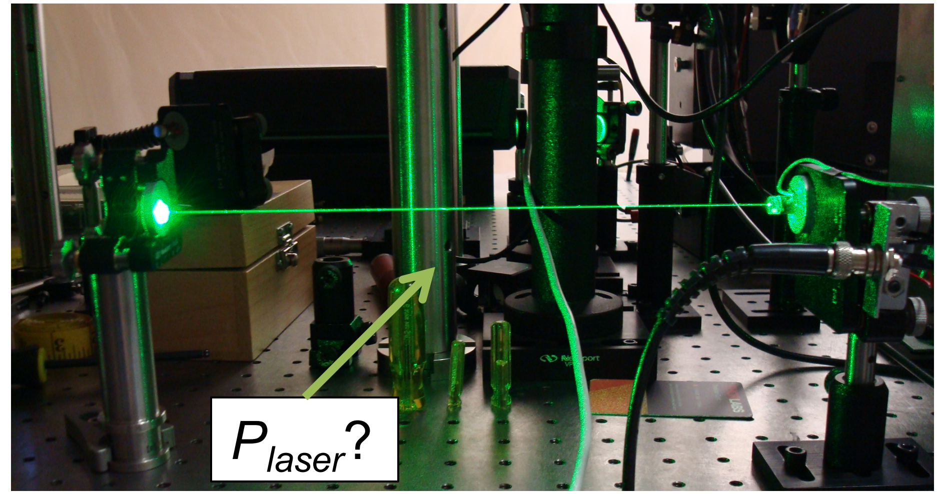


Practical challenges:
→ Cavity must live in beamline vacuum
→ Laser + optics must (?) live in hall, everything must be controlled remotely
→ Remote alignment of laser into cavity

Laser Polarization - the Transfer Function

Knowledge of the laser polarization inside cavity is a key systematic uncertainty
→ In the past, polarization was inferred from measurements of beam transmitted through cavity, after 2nd mirror





Typically a "transfer function" was measured with cavity open to air

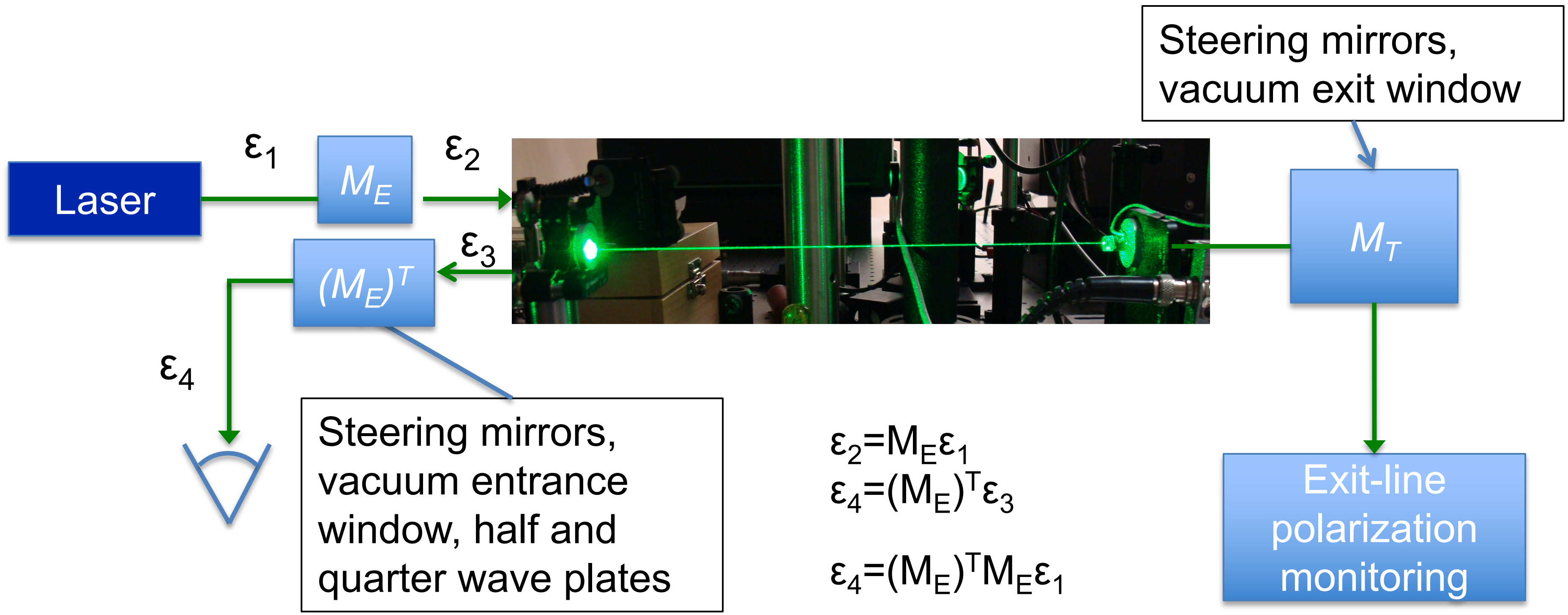
<u>Possible complications due to:</u>
→ Change in birefringence due to mechanical stresses (tightening bolts)
→ Change in birefringence when pulling vacuum

Laser Polarization – the “Entrance” Function

Propagation of light into the Fabry-Pérot cavity can be described by matrix, $\boldsymbol{M_E}$

→ Light propagating in opposite direction described by transpose matrix, $(\boldsymbol{M_E})^T$

→ If input polarization (ε_1) linear, polarization at cavity (ε_2) circular only if polarization of reflected light (ε_4) linear and orthogonal to input*



$$\varepsilon_2 = M_E \varepsilon_1$$
$$\varepsilon_4 = (M_E)^T \varepsilon_3$$

$$\varepsilon_4 = (M_E)^T M_E \varepsilon_1$$

Cavity Polarization via Reflected Power

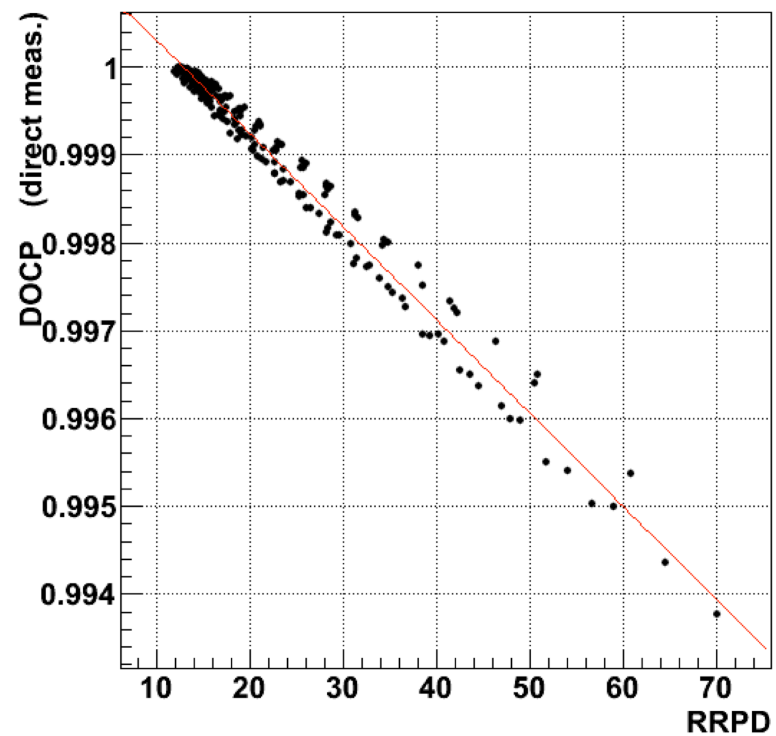
"If input polarization (ε_1) linear, polarization at cavity (ε_2) circular only if polarization of reflected light (ε_4) linear and orthogonal to input"

→ In the context of the Hall C system, this means that the circular polarization at cavity is maximized when retro-reflected light is minimized

→ Above statement was verified experimentally (with cavity open) by directly measuring circular polarization in cavity while monitoring retro-reflected power

→ Additionally, by fitting/modeling the entrance function we can determine the degree of circular polarization by monitoring the reflected power – even for the case when system is not optimized

Circular polarization in cavity

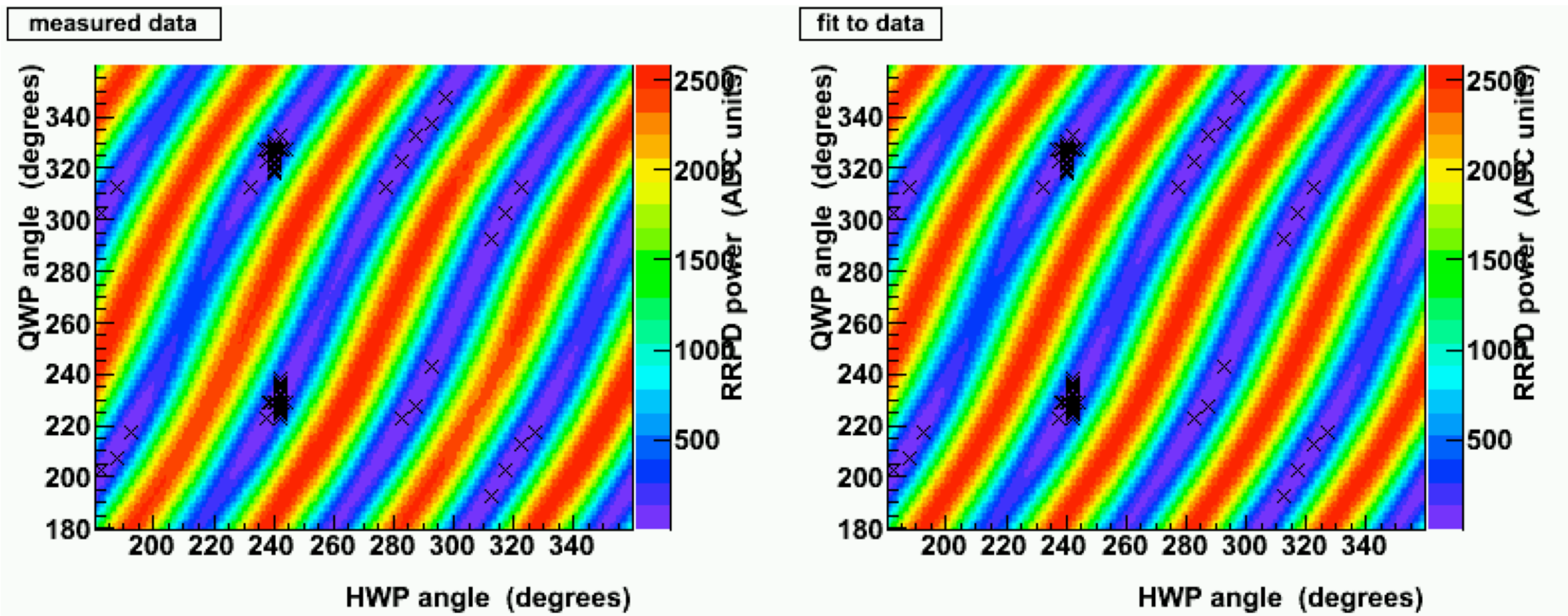


Reflected Power Scans

Using a combination of half and quarter wave plates, we can build an arbitrary polarization state

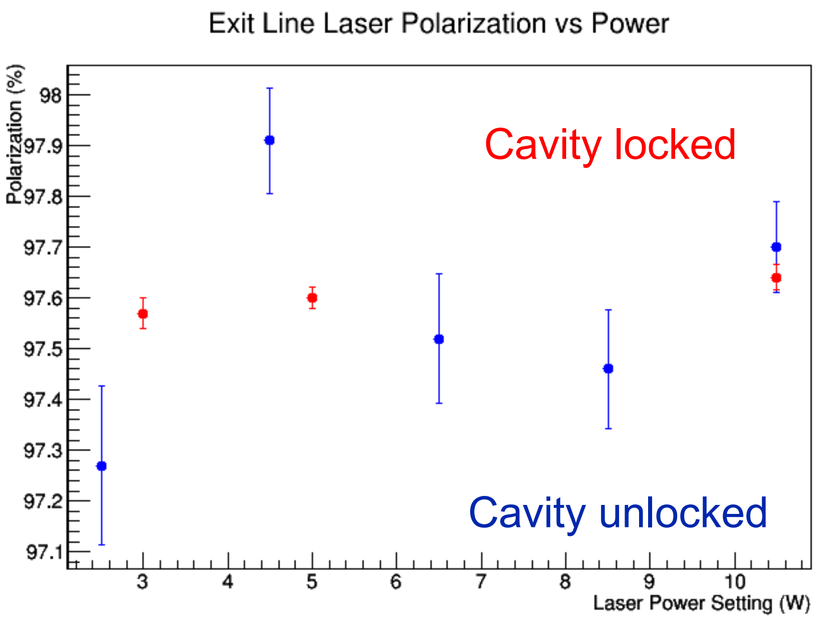
→ Scanning this polarization phase space and monitoring the retro-reflected power, we can build a model for the entrance function, M_E

→ Free parameters include variations to HWP and QWP thicknesses, arbitrary element with non-zero birefringence



Using this entrance function, we can determine the laser polarization inside the cavity for an arbitrary input state

Laser Polarization Systematic Uncertainty



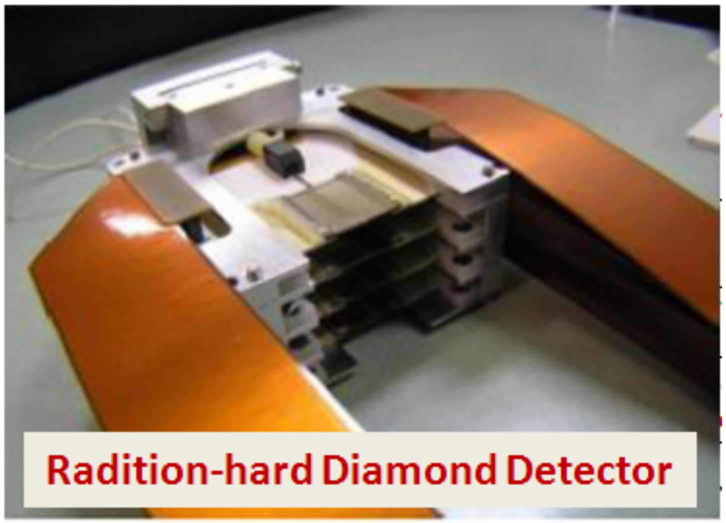
Cavity polarization optimization scans performed with cavity unlocked
→ No measureable difference in laser polarization when comparing to locked cavity

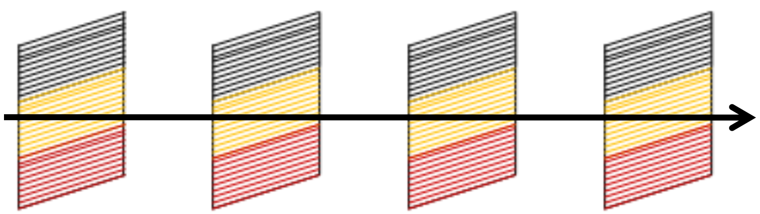
Additional sources of potential uncertainty due to transmission through input cavity mirror and potential laser depolarization
→ Both constrained by measurement to be very small

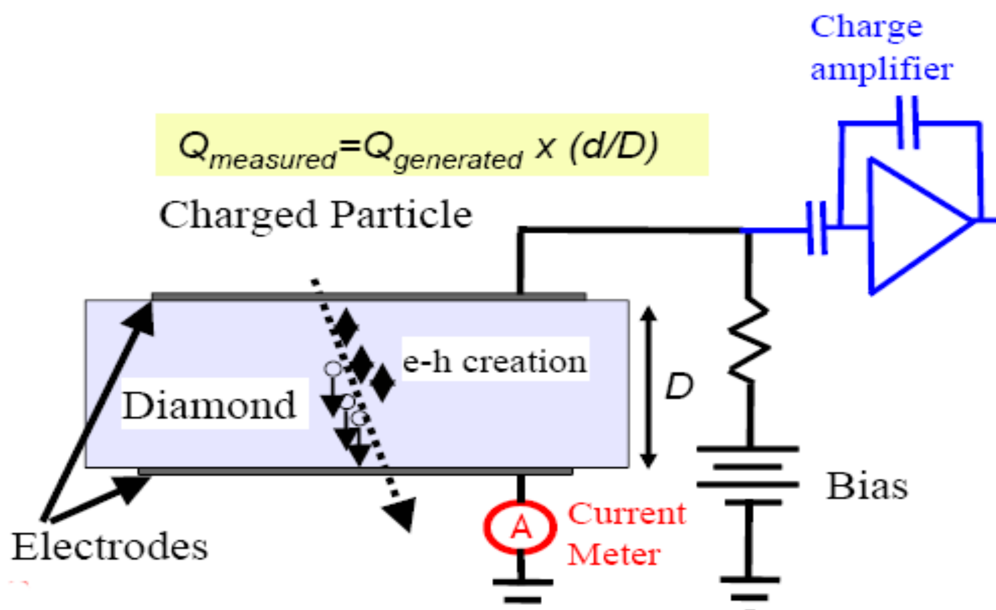
Overall systematic error on laser polarization in cavity ~ 0.1%

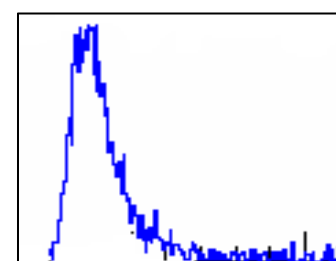
Compton Electron Detector

Diamond microstrips used to detect scattered electrons
→ Radiation hard
→ Four 21mm x 21mm planes each with 96 horizontal 200 μm wide micro-strips.
→ Rough-tracking based/coincidence trigger suppresses backgrounds



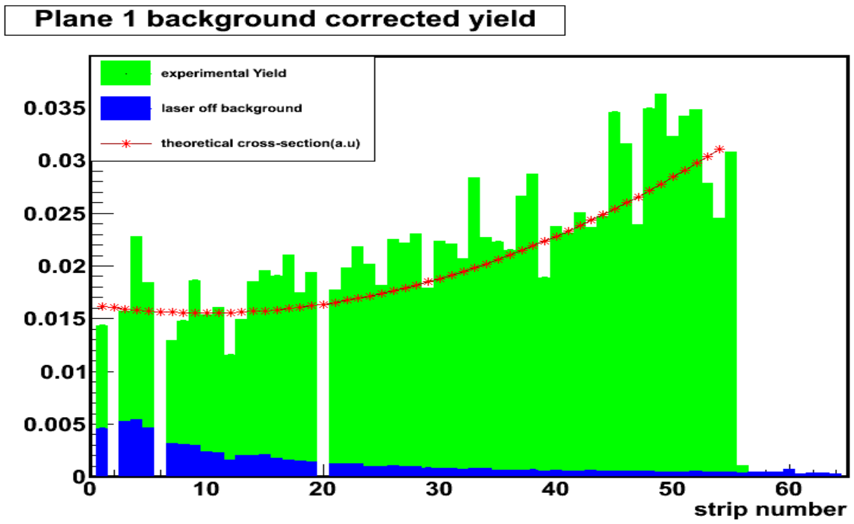


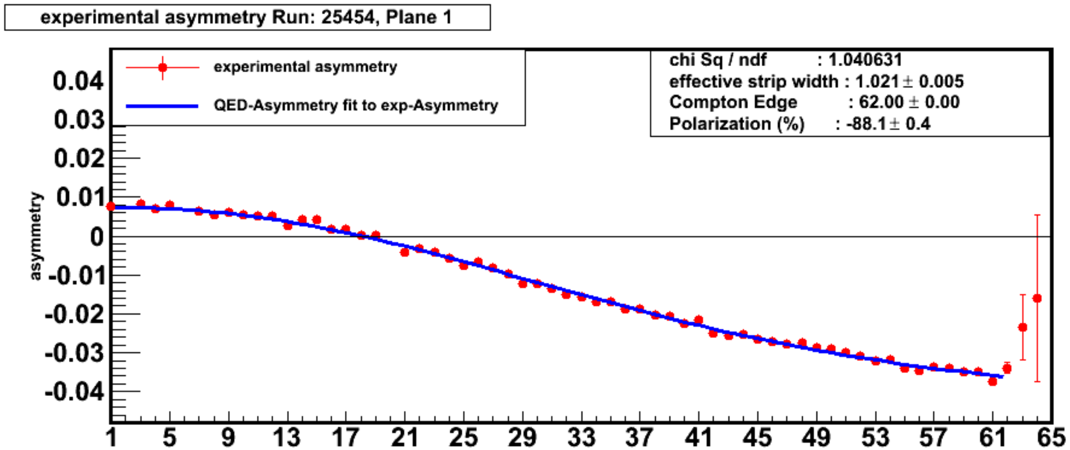




Compton Electron Detector Measurements

Polarization analysis:
→ Yield for each electron helicity state measured in each strip
→ Background yields measured by "turning off" (unlocking) the laser
→ Asymmetry constructed in each strip





Strip number corresponds to scattered electron energy
→ Endpoint and zero-crossing of asymmetry provide kinematic scale
→ 2-parameter fit to beam polarization and Compton endpoint

Hall C Electron Detector Systematic Uncertainties

Precision requires precise knowledge of chicane properties
- → Dipole fields
- → Detector position

Hall C detector uncertainty dominated by DAQ related issues
- → Timing issue in FPGA-based readout lead to rate dependent inefficiency
- → Can be improved with new firmware

=3

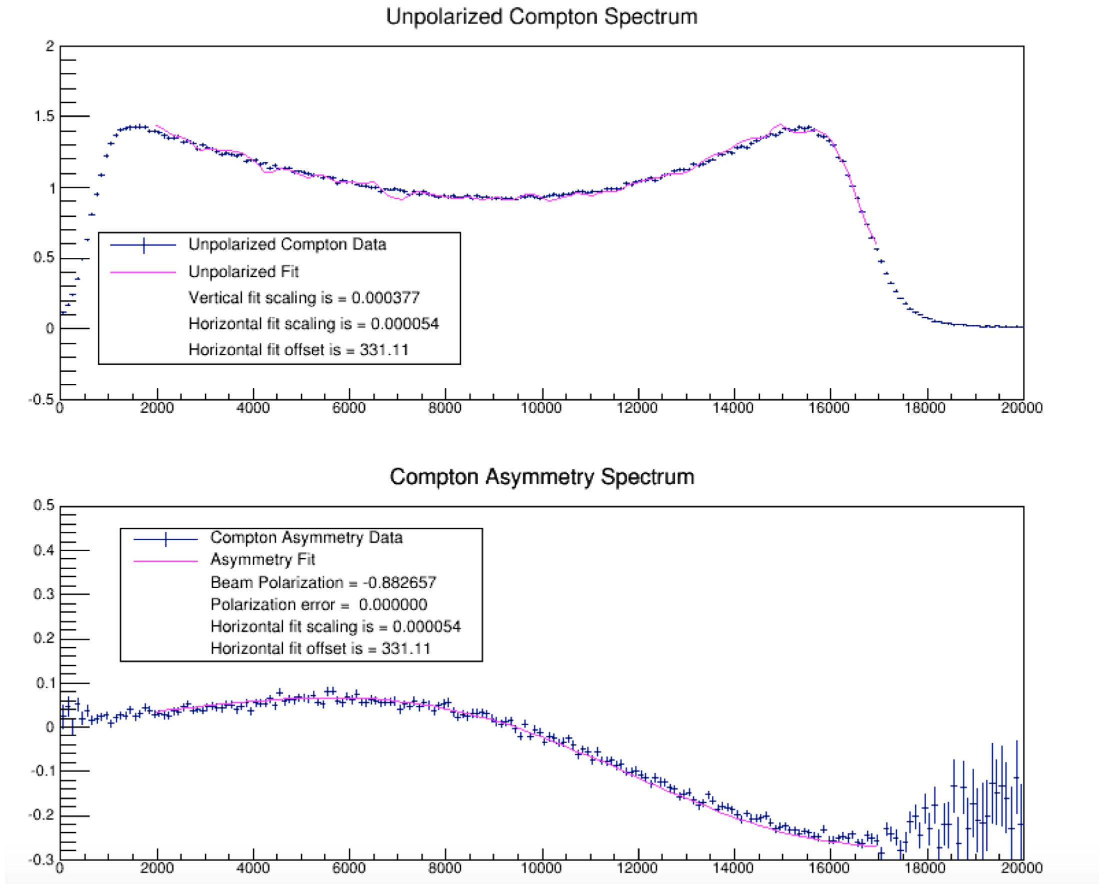
Source	Uncer-tainty	$\Delta P/P$ (%)
Laser polarization	0.18 %	0.18
3^{rd} Dipole field	0.0011 T	0.13
Beam energy	1 MeV	0.08
Detector Z position	1 mm	0.03
Trigger multiplicity	1-3 plane	0.19
Trigger clustering	1-8 strips	0.01
Detector tilt (X)	1°	0.03
Detector tilt (Y)	1°	0.02
Detector tilt (Z)	1°	0.04
Strip eff. variation	0.0 - 100%	0.1
Detector Noise	$\leq$20% of rate	0.1
Fringe Field	100%	0.05
Radiative corrections	20%	0.05
DAQ ineff. correction	40%	0.3
DAQ ineff. pt-to-pt		0.3
Beam vert. angle variation	0.5 mrad	0.2
helicity correl. beam pos.	5 nm	< 0.05
helicity correl. beam angle	3 nrad	< 0.05
spin precession through chicane	20 mrad	< 0.03
Total		0.59

A. Narayan et al, Phys.Rev. X6 (2016) no.1, 011013

Photon Detector Analysis

Historically, beam polarization from photon detector often extracted by fitting the shape of the asymmetry
→ Extremely sensitive to detailed understanding of detector response, resolution
→ Knowledge of threshold a key issue

Choice of detector depends on energy regime



ADC units → Photon energy

At high energies, lead glass or lead tungstate appropriate – at lower energies, CsI, NaI, more recently GSO

Hall A Compton – Photon Detector Upgrade

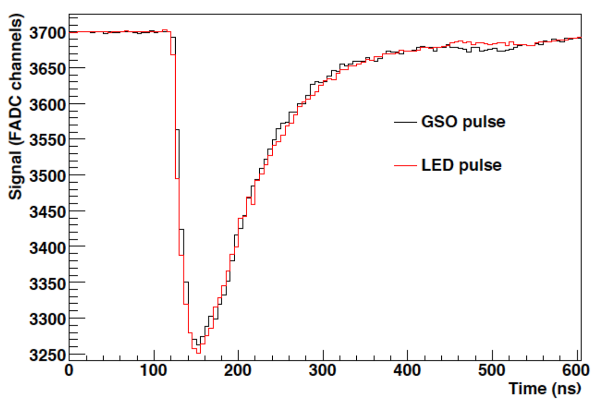
Spearheaded by Carnegie Mellon U.

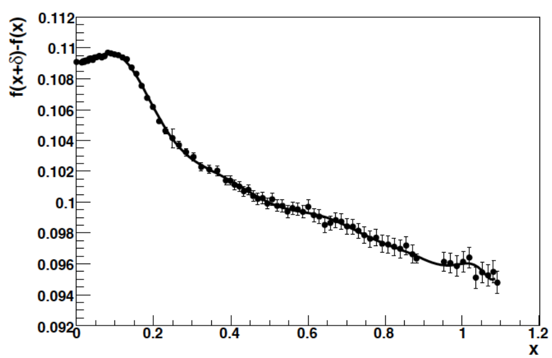
New detector (GSO) for low energy – new technique

Uncertainties can be significantly reduced using energy weighted asymmetry

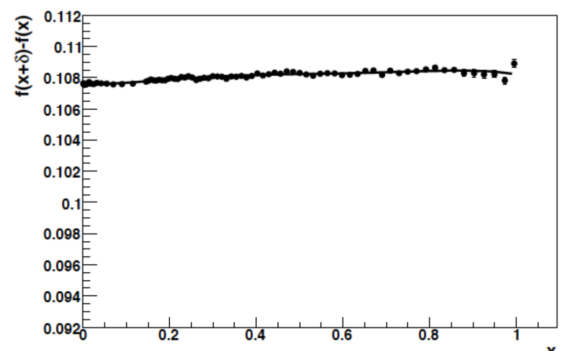
$$E^{\pm} = LT\int_0^{E_{\max}} \varepsilon(E)E\frac{d\sigma}{dE}(E)\left(1 \pm P_e P_\gamma A_l(E)\right)dE \longrightarrow A_{Exp} = \frac{E^+ - E^-}{E^+ + E^-}$$

→ No threshold, so analyzing power well understood
→ Less sensitive to understanding detector resolution
→ Understanding detector non-linearity over relevant range of signal size most significant challenge → LED pulser system





Poor Linearity



Good Linearity

Photon Detector – Systematic Errors

Systematic uncertainty < 1%, even with large contribution from laser polarization

Excluding laser polarization, total uncertainty < 0.5%

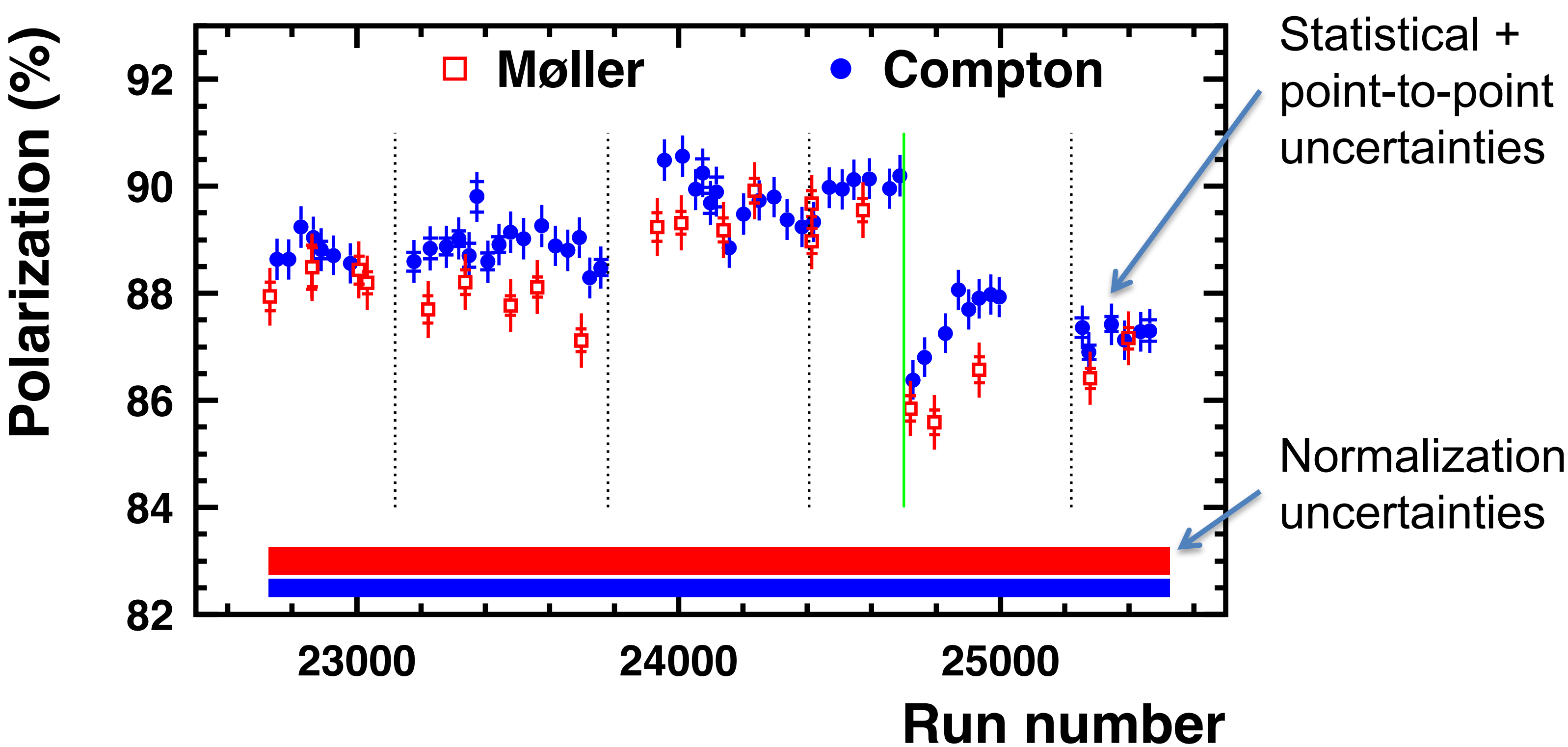
Systematic Errors	
Laser Polarization	0.80%
Signal Analyzing Power:	
Nonlinearity	0.30%
Energy Uncertainty	0.10%
Collimator Position	0.05%
Analyzing Power Total Uncertainty	0.33%
Gain Shift:	
Background Uncertainty	0.31%
Pedestal on Gain Shift	0.20%
Gain Shift Total Uncertainty	0.37%
Total Uncertainty	0.94%

HAPPEX-III

M. Friend, et al, NIM A676 (2012) 96-105

Polarization Measurements

Q-Weak Run 2



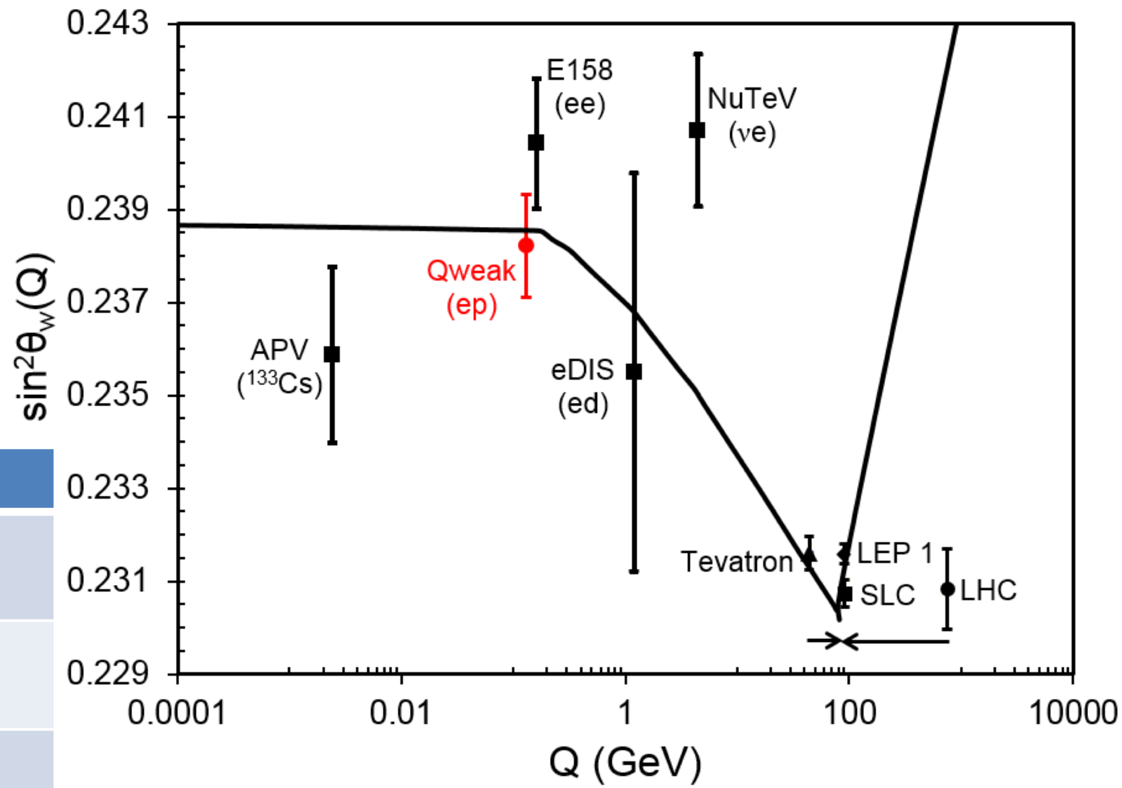
Compton and Møller results agree to ~ 0.7% → combined norm. unc. = 0.77%

Using weighted average of both polarimeters, polarization unc. for Q-Weak = 0.61%

Precision Polarimetry and Running of the Weak Mixing Angle $\sin^2\theta_W$

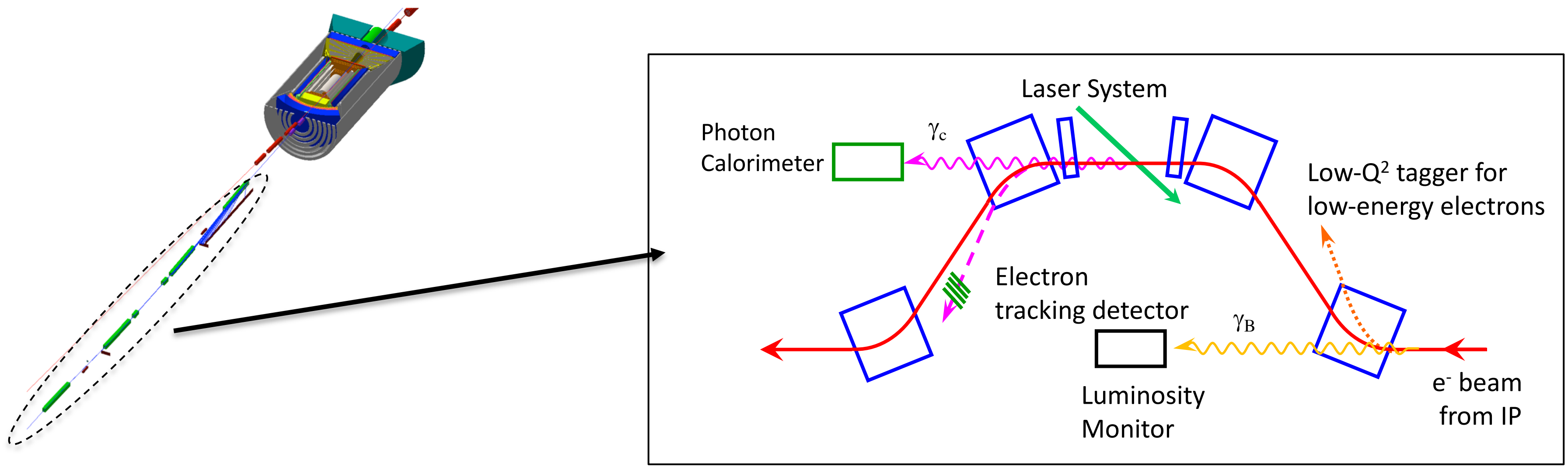
Precision measurements of the running of weak mixing angle sensitive to new physics beyond Standard Model
→ Beam polarization a crucial systematic uncertainty

Quantity	Uncertainty (ppb)
Charge Normalization	2.3
Beamline background	1.2
Beam asymmetries	1.2
Rescattering bias	3.4
Beam polarization	1.2
Target windows	1.9
Kinematics	1.3
Others (combined)	2.2
Total uncertainty	5.6



New results forthcoming from Q-Weak experiment in Hall C
→ More information from MOLLER (ee) and SOLID (PVDIS) experiments
→ Require even higher precision from polarization measurements

Compton Polarimetry at JLEIC



- Work is underway to develop a Compton polarimeter design for use at a future electron-ion collider → desired precision on the order of 1%
- JLEIC electron beam parameters: 3-10 GeV, 476 MHz, beam currents of order ~1 A
- Design based on successful JLab Hall A and Hall C polarimeters
  - Focusing on electron detection for now
- Some desire to measure polarization of each bunch individually- this would require
  - RF pulsed laser system
  - Fast electron detector
- Simultaneous sensitivity to transverse beam polarization would be a bonus

Summary

- Compton polarimetry an important tool for nuclear physics experiments at JLab
  - Highest precision generally required by PVES program
- Relatively low currents, CW beam at JLab required novel laser solution
  - Laser coupled to moderate/high gain FP cavity
  - Knowledge of laser polarization in cavity was a challenge in the past → no longer significant source of uncertainty
- Electron and photon detection provide quasi-independent measurements of polarization with different systematic uncertainties
  - Choice of detector technology driven by beam energy, polarimeter properties, expected integrated luminosity
- Application at future EIC may provide new technical challenges
  - High currents provide high rates, but large backgrounds as well

EXTRA

JLab Polarimetry Techniques

- Three different processes used to measure electron beam polarization at JLab
  - Møller scattering: $\vec{e} + \vec{e} \rightarrow e + e$, atomic electrons in Fe (or Fe-alloy) polarized using external magnetic field
  - **Compton scattering**: $\vec{e} + \vec{\gamma} \rightarrow e + \gamma$, laser photons scatter from electron beam
  - Mott scattering: $\vec{e} + Z \rightarrow e$, spin-orbit coupling of electron spin with (large Z) target nucleus
- Each has advantages and disadvantages in JLab environment

Method	Advantage	Disadvantage
Compton	Non-destructive, precise	Can be time consuming, systematics energy dependent
Møller	Rapid, precise measurements	Destructive, low current only
Mott	Rapid, precise measurements	Does not measure polarization at the experiment

Evolution of Precision Polarimetry at Jefferson Lab

Experiment	Year	dA/A	dP/P	dP/P (Moller)	dP/P (Compton)
HAPPEX-1	1999	7.2%	3.2%	3.2	3.3
G0	2003	10-30%	1.4%	1.4%	N/A
HAPPEX-2	2005	4-8%	1%	2-3%	1%
PREX	2010	9.4% (3%*)	1.1%	1.2%	1.1%
Q-WEAK	2010-12	4%	0.61%	0.85%	0.59%
MOLLER		2%*	0.4%		
SOLID-PVDIS		0.6%*	0.4%		

*Future experiments

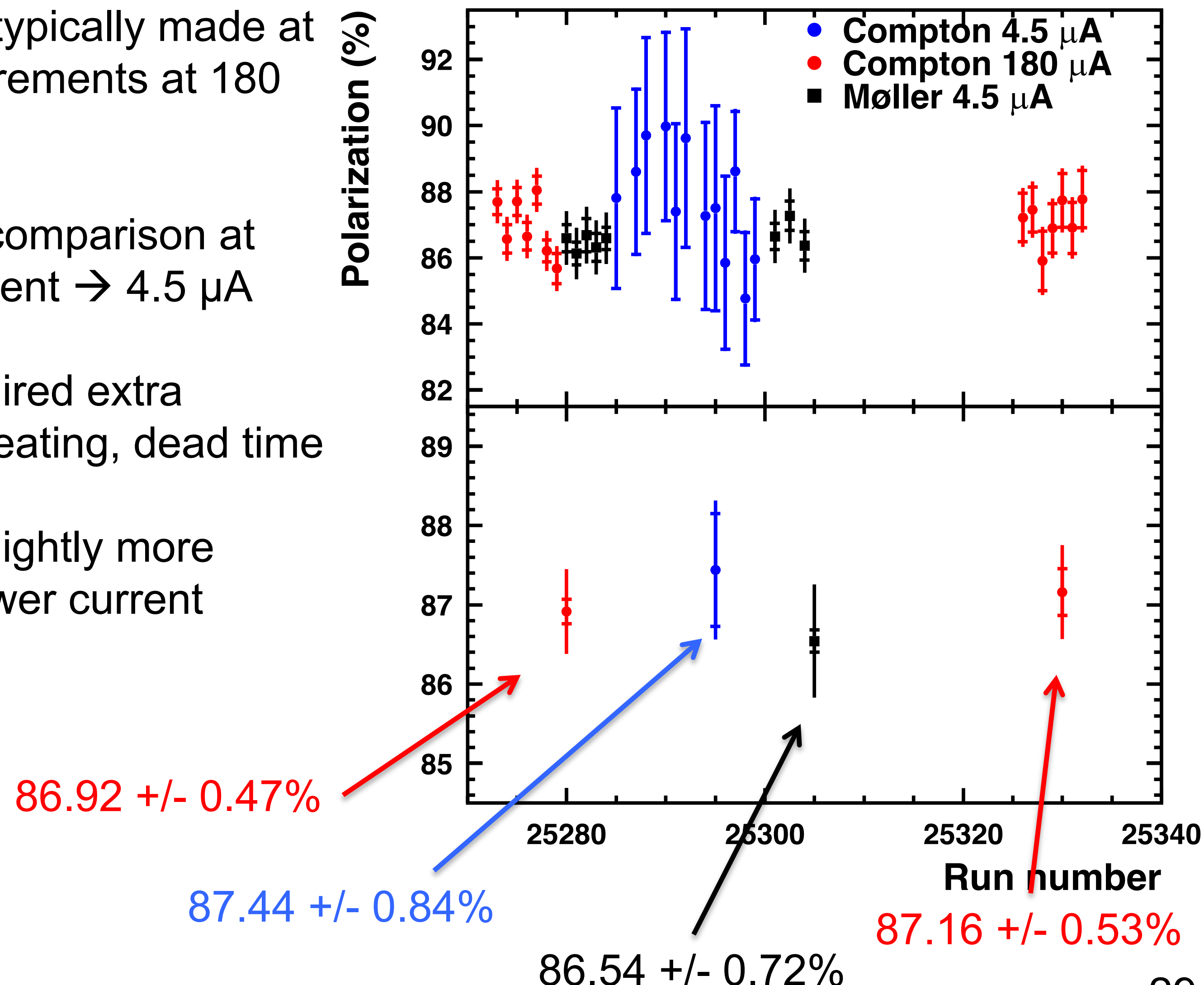
Møller-Compton Cross Calibration

Møller measurements typically made at 1 μA, Compton measurements at 180 μA

→ Performed a direct comparison at the same beam current → 4.5 μA

→ Møller analysis required extra corrections for beam heating, dead time

→ Compton analysis slightly more sensitive to noise at lower current



Polarization Measurement Times

Luminosity for Compton scattering at non-zero crossing angle:

$$\mathcal{L} = \frac{(1+\cos\alpha_c)}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_L \lambda}{hc^2} \frac{1}{\sqrt{\sigma_e^2 + \sigma_\gamma^2}} \frac{1}{\sin\alpha_c}$$

Positron beam size at interaction point with laser dictates luminosity (for given beam current and laser/electron beam crossing angle)

Time for measurement of precision $\Delta P/P$:

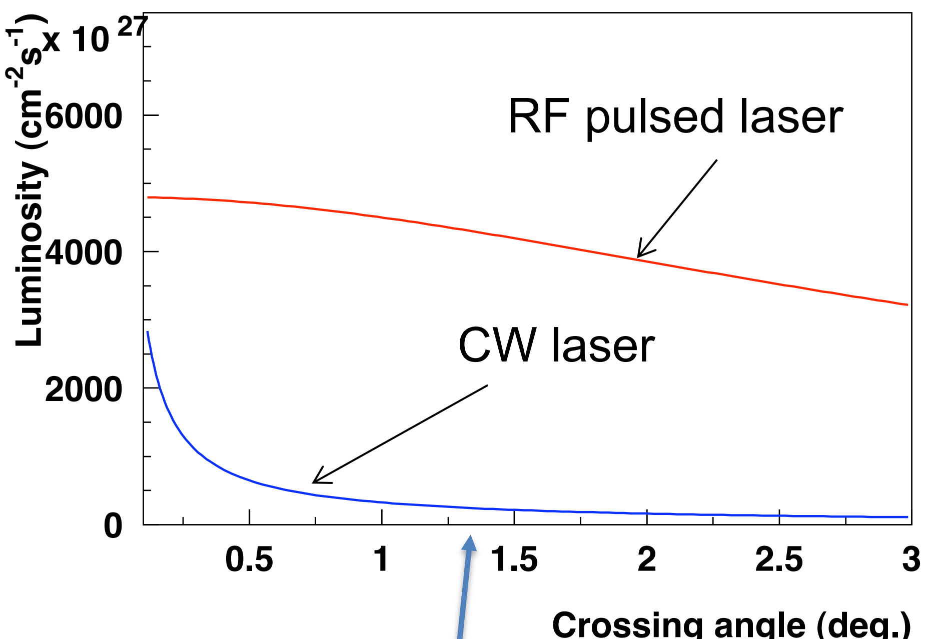
$$t^{-1} \approx \mathcal{L}\sigma \left(\frac{\Delta P}{P}\right)^2 P_e^2 < A^2 >$$

This expression is a little too simple – ignores fit uncertainties, additional degrees of freedom

RF pulsed FP Cavity

$$\frac{L_{pulsed}}{L_{CW}} \approx \frac{c}{f\sqrt{2\pi}}\left(\sqrt{\sigma^2_{c\tau,laser}+\sigma^2_{c\tau,e}+\frac{1}{\sin^2(\alpha/2)}\left(\sigma_e^2+\sigma^2_{laser}\right)}\right)^{-1}$$

JLab beam → 499 MHz, $\Delta\tau$~0.5 ps



Hall A/C lasers

Luminosity from pulsed laser drops more slowly with crossing angle than CW laser

→ FP cavity pumped by mode-locked laser at beam frequency could yield significantly higher luminosity

→ More complicated system – R&D required

RF pulsed cavities have been built – this is a technology under development for ILC among other applications