# High Precision Electron Polarimetry

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**Mississippi State University**

**Spin 2014,**
**Beijing**
**Oct 20-24, 2014**

# Outline

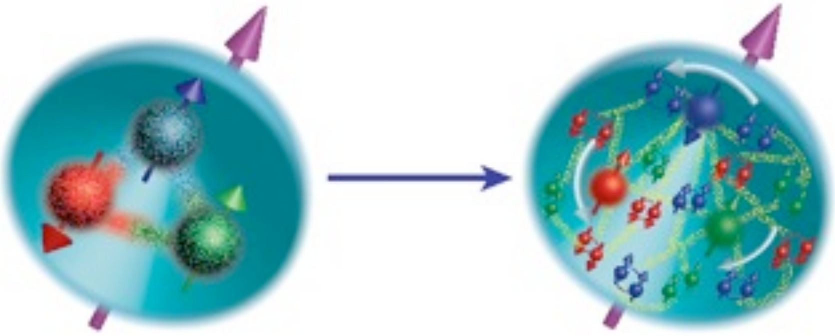
- Motivations for Precision e-Polarimetry
- Desired Properties
- Polarimetry Techniques
    1. Mott
    2. Transmission
    3. Møller
    4. Compton
- Recent Developments & Results
- Future Possibilities
- Summary

# Motivations

## Spin polarized electrons have allowed us to:

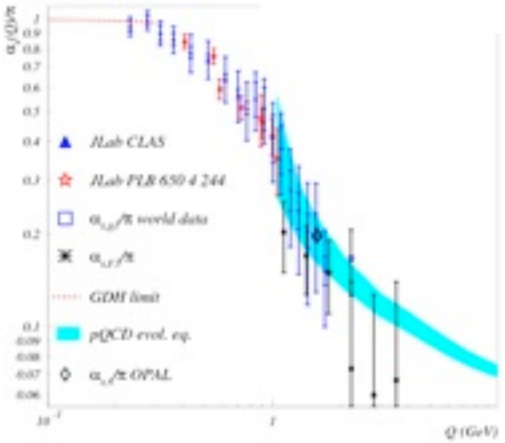
### study the internal structure of nucleons

**form factors**
**spin structure of nucleons**
**3-D mapping of nucleons**



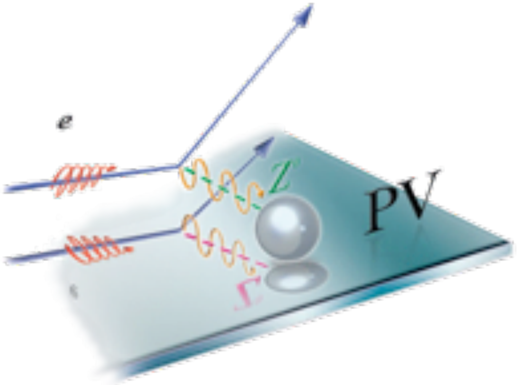
### fundamental tests of QCD

**Bjorken sum rule**
**GDH sum rule**



### test of the SM in search of "New Physics"

**Parity violating electron scattering (PVeS)**



**knowledge of the electron beam polarization is one of the major sources of uncertainty for this entire program.**

# PVeS: a Case Study

PVeS Experiment Summary

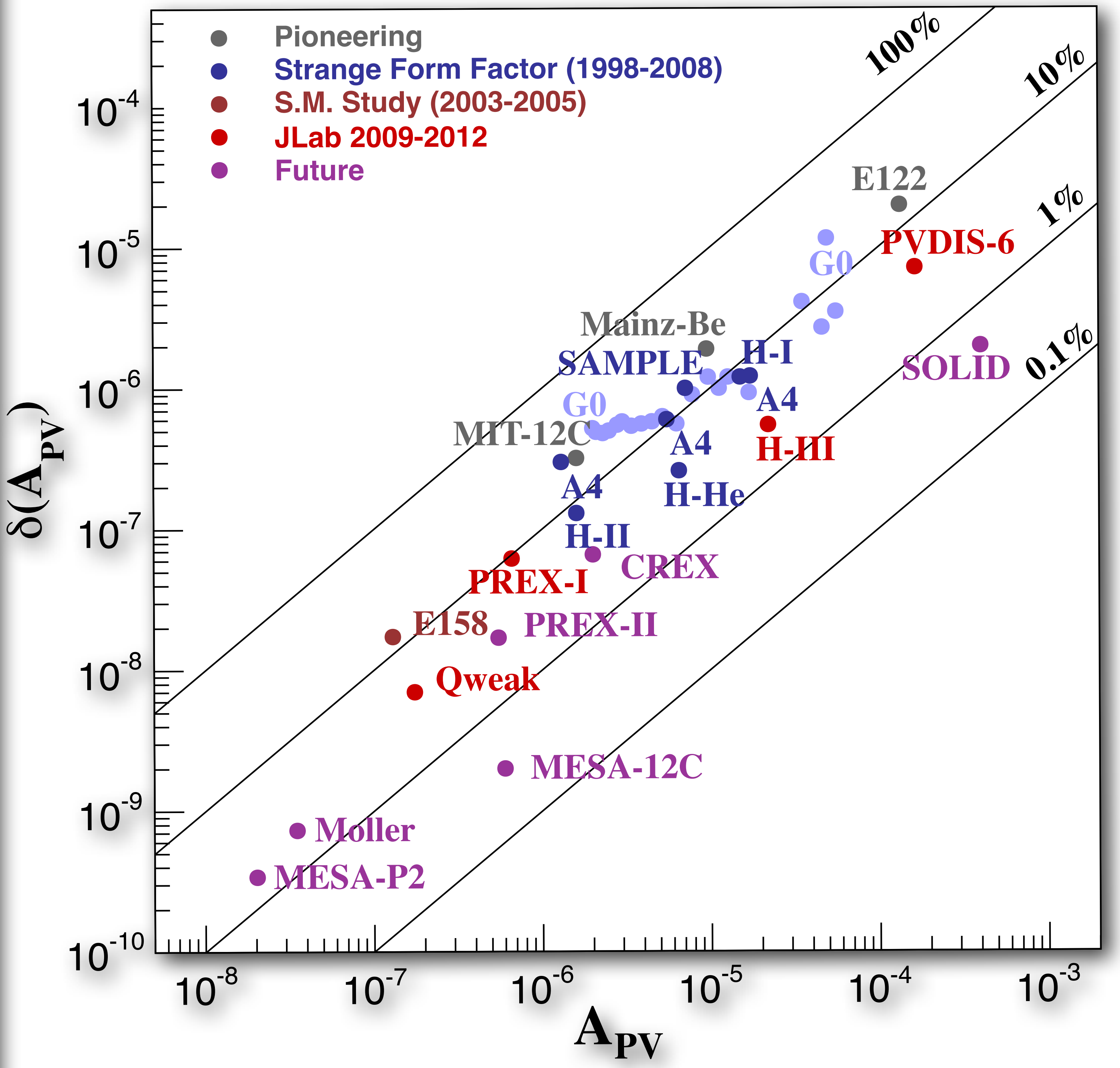


Figure: Courtesy of K. Paschke

**Precision PVeS made possible by decades of technical progress in:**

**polarized sources,**
**electron polarimetry**
**nanometer beam stability,**
**high power targets,**
**low noise electronics &**
**radiation hard detectors.**

**Future program requires sub-1% electron polarimetry**

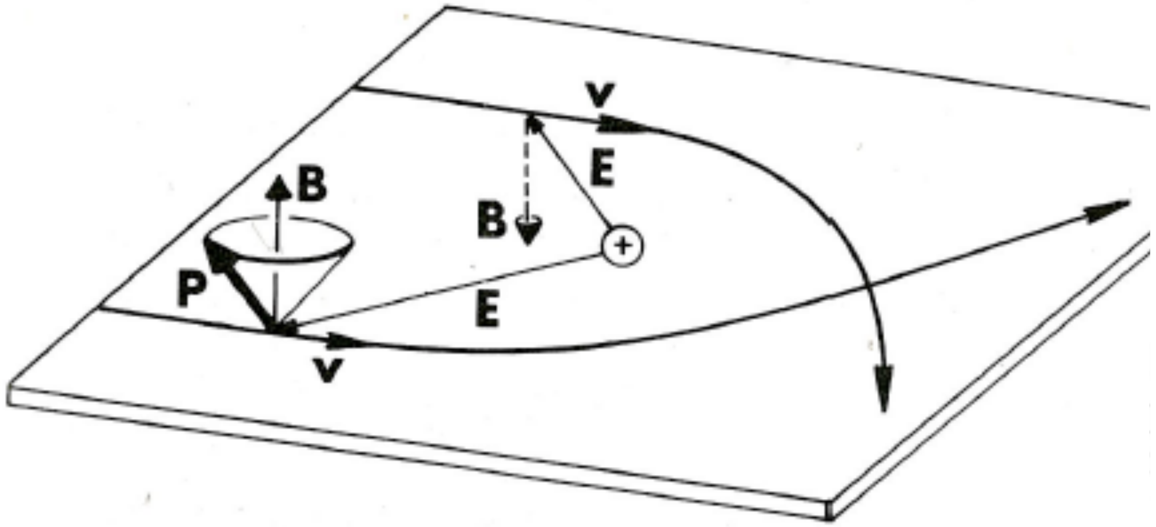
# Electron Polarimetry Desirables

- Large rates → rapid measurement cycle, shorter than the typical time over which polarization changes
- Uses the same beam (energy, current, location) as the experiment
- Large, well known and slowly varying analyzing power
- Continuous measurement, non-invasive to experiment
- Stable, highly polarized targets
- target polarization easily measurable
- high efficiency detectors with well understood and stable acceptances

# Techniques: Mott Polarimeters

## Mott scattering of polarized electrons:

N.F. Mott and H.S.W. Massey, Theory of Atomic Collision, (Clarendon Press, Oxford, 1965)



**Analyzing power based on the spin-orbit coupling between the electron's spin and its motion in the nuclear Coulomb field.**

**eA cross section is given by** $$\sigma(\theta) = I(\theta)\left[1 + S(\theta)\mathbf{P}\cdot\mathbf{n}\right]$$

$$\mathbf{n} = \frac{\mathbf{k}\times\mathbf{k}'}{|\mathbf{k}\times\mathbf{k}'|}$$

***I(θ)*** **= spin averaged cross section**
***S(θ)*** **= Sherman function**

scattering of unpolarized electrons produces a net polarization

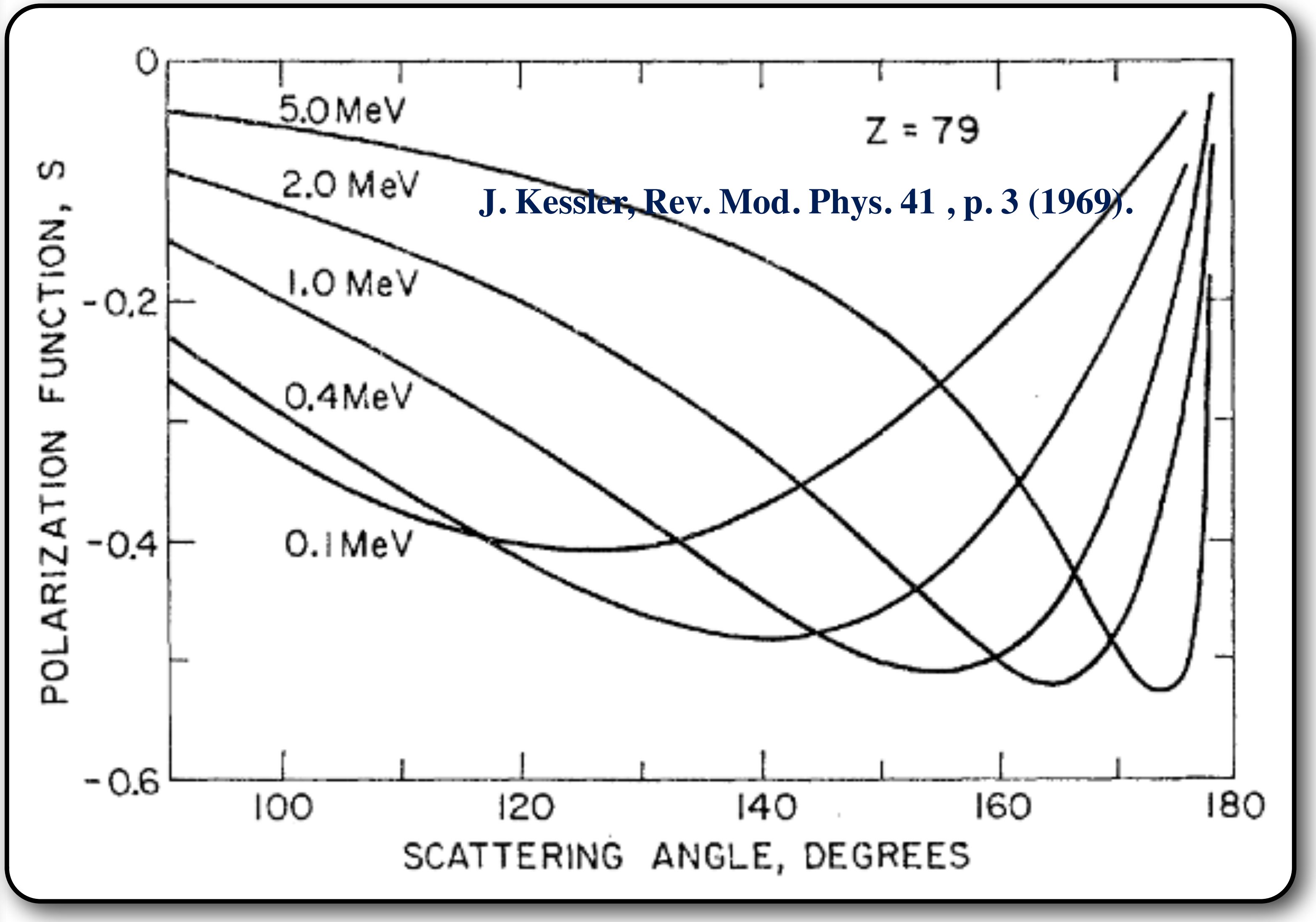
$$\mathbf{P}(\theta) = \frac{\sigma_\uparrow(\theta) - \sigma_\downarrow(\theta)}{\sigma_\uparrow(\theta) + \sigma_\downarrow(\theta)} = S(\theta)\mathbf{n}$$

polarized electrons produce a left-right asymmetry

$$\boxed{A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = S(\theta)\mathbf{P}\cdot\mathbf{n}}$$

**Can be used to measure polarization transverse to the scattering plane**

# Mott Polarimeters



J. Kessler, Rev. Mod. Phys. 41 , p. 3 (1969).

**Calculated analyzing power for single free atom (Sherman function)**

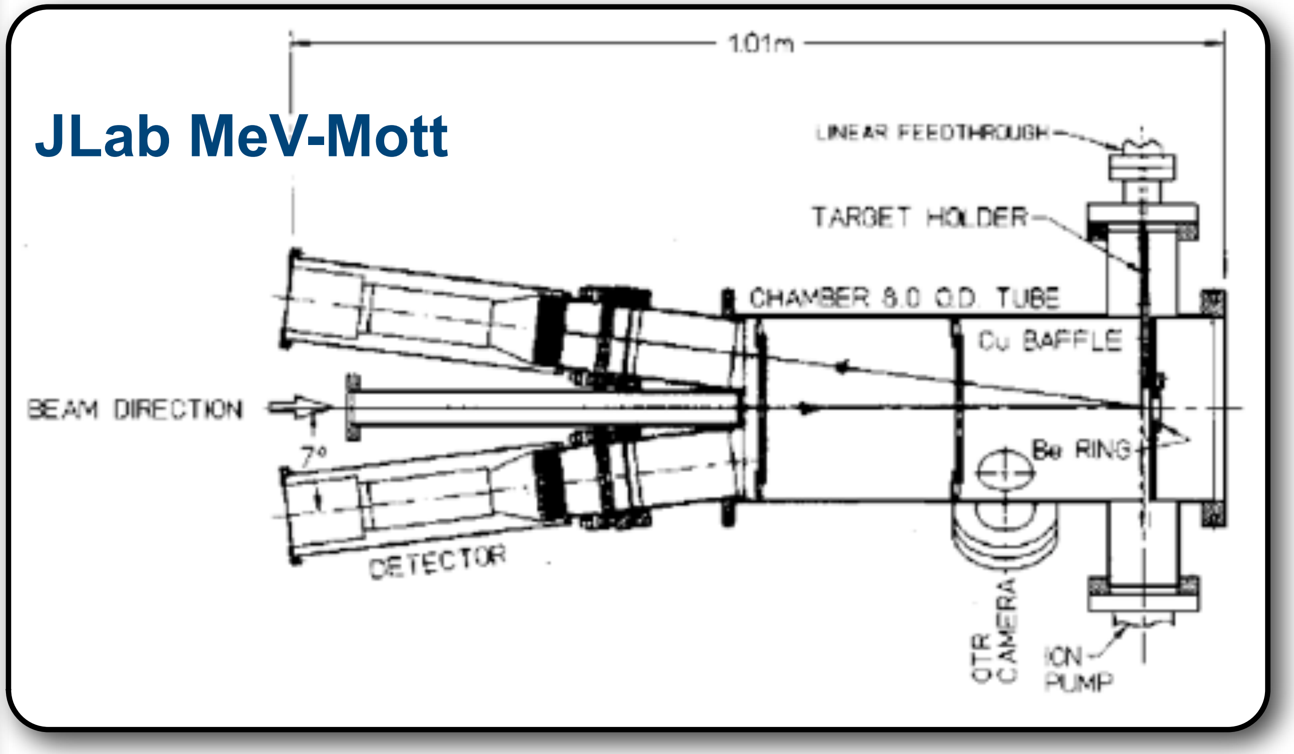
**Real targets of finite thickness lead to plural scattering - a major source of uncertainty is the effective analyzing power**

**cross sections at lower beam energies, are very large, requiring very low-average beam currents and exceptionally thin targets**

**Above ~10 MeV, the cross section is too small, and the scattering angle for maximum analyzing power is too close to $180^0$.**

# Mott Polarimeters

**Mott polarimeters are routinely used with beam energies no greater than 100 to 120 keV but there are only two MeV-Mott polarimeters**



**JLab MeV-Mott**

**MeV Motts have advantages**

**smaller x-sections**

$\Downarrow$

**less plural scattering**
**higher beam currents**

$\Downarrow$

**smaller analyzing power uncertainties**
**better beam monitoring**

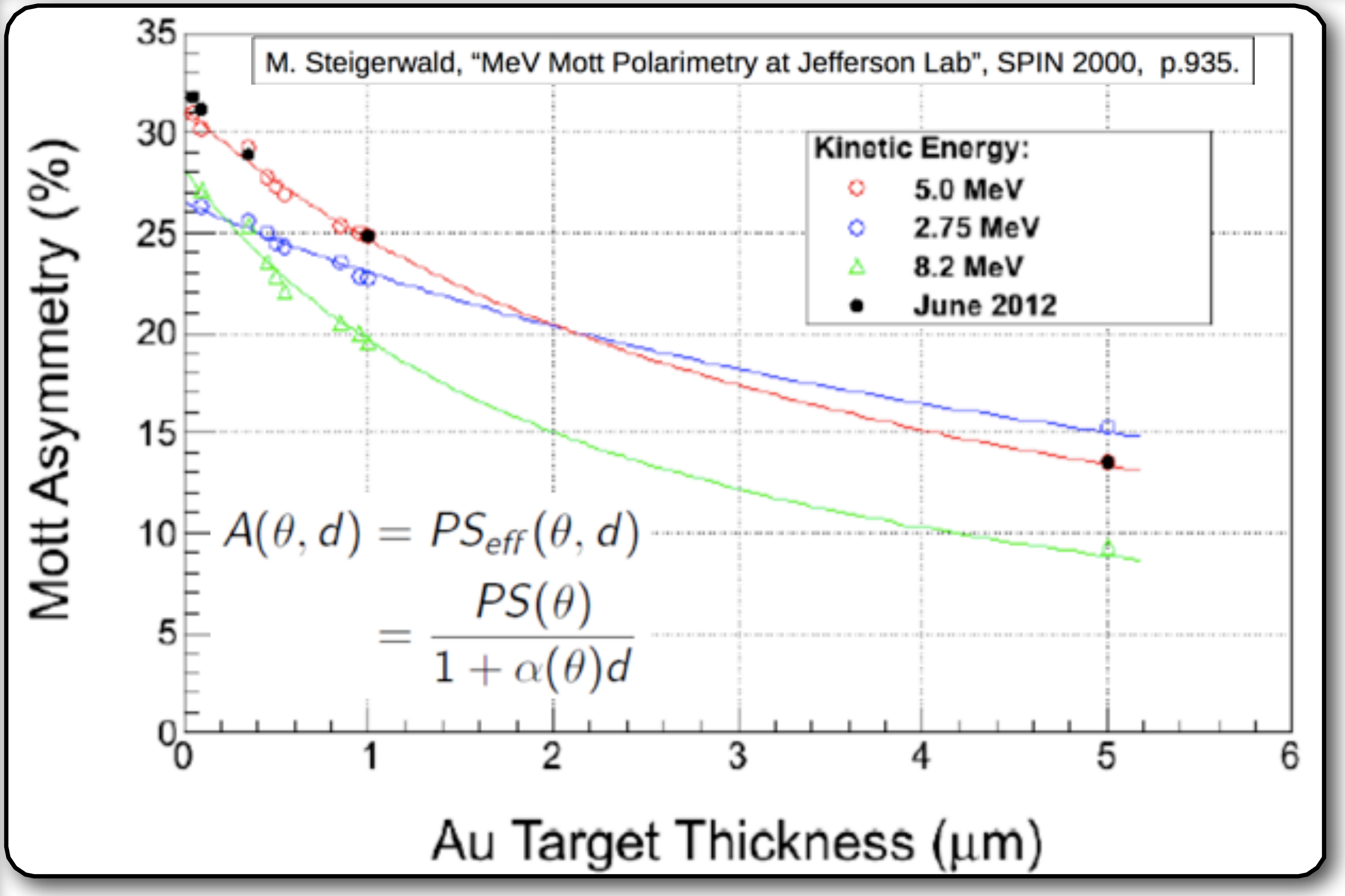
**cross-ratio method**

**LR cross ratio defined as:** $r = \sqrt{\frac{N_L^{\uparrow} N_R^{\downarrow}}{N_l^{\downarrow} N_R^{\uparrow}}}.$ **and asymmetry** $A_{LR} = \frac{1-r}{1+r}.$

**The polarization is** $\mathbf{P} = \frac{1}{|S_{eff}(\theta)} \left[ A_{LR}\hat{\mathbf{y}} - A_{UD}\hat{\mathbf{x}} \right]$

Cross-ratio method cancels false asymmetries from detector efficiency, beam current, target thickness and solid angle.

# Precision Mott Polarimeters



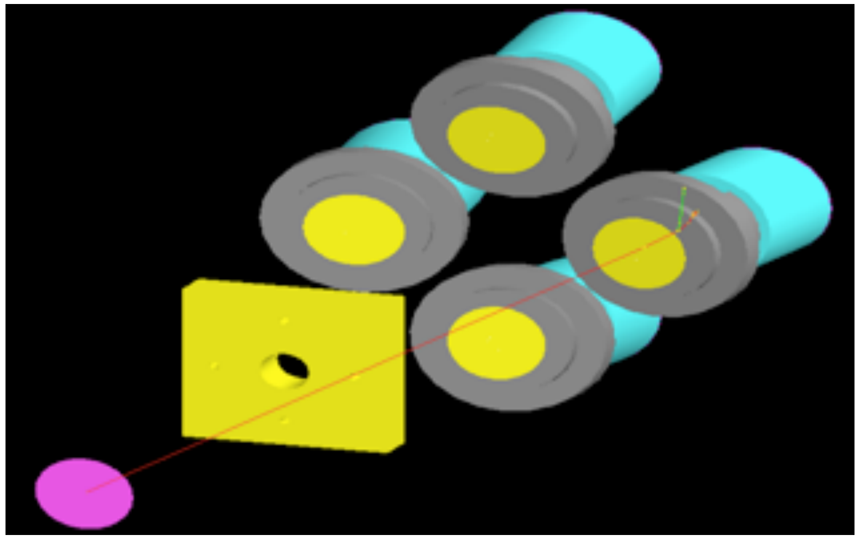
**published absolute uncertainty 1.1%**

**ΔP dominated by ΔS**

**Uncertainty in extrapolation to single atom (d=0) dominates ΔS**

**Effort underway to improve uncertainty of MeV Mott to < 1%**

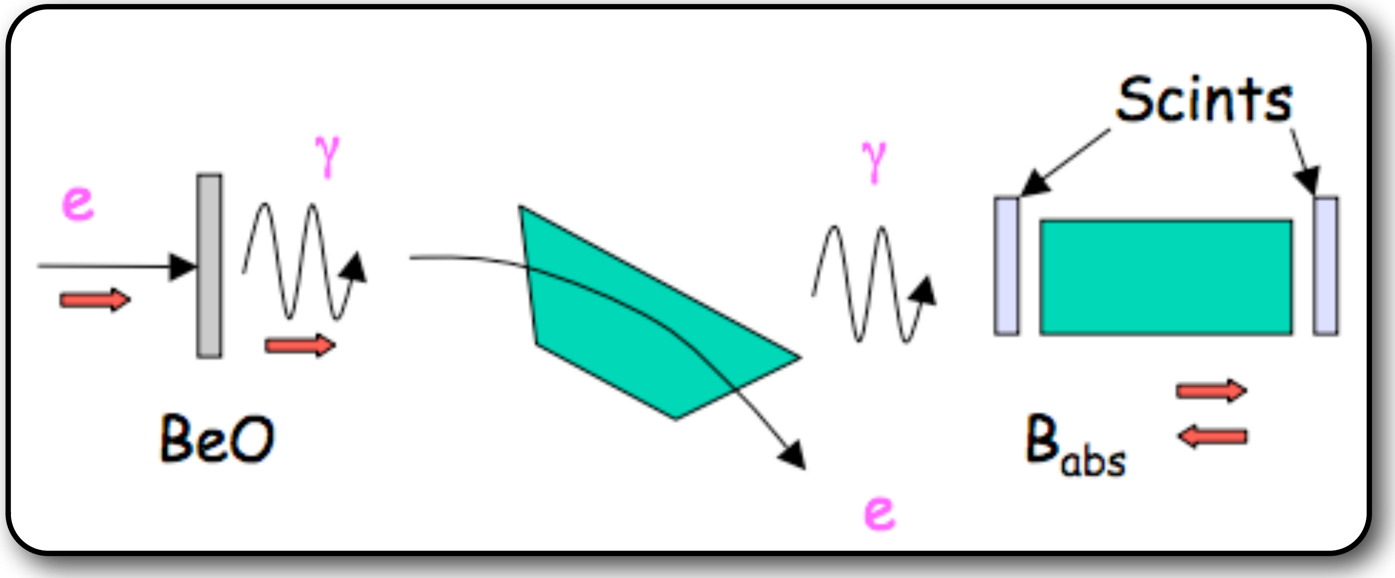
**strategy: more accurate modeling of the Sherman function extrapolation to zero thickness using GEANT4**

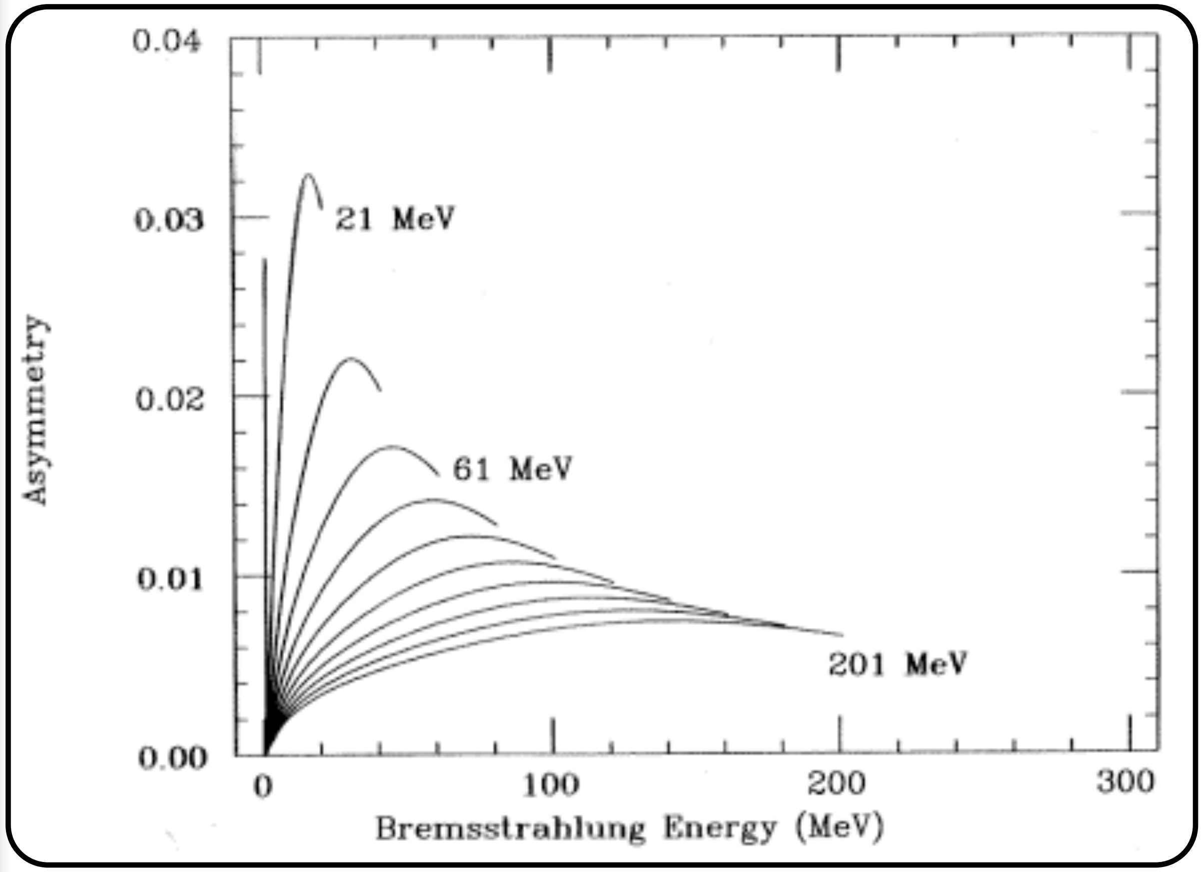


# Transmission Polarimeters

- Polarized electrons transfer polarization to photons

- Measure the asymmetry in transmission of photons through iron magnet for opposite polarity.





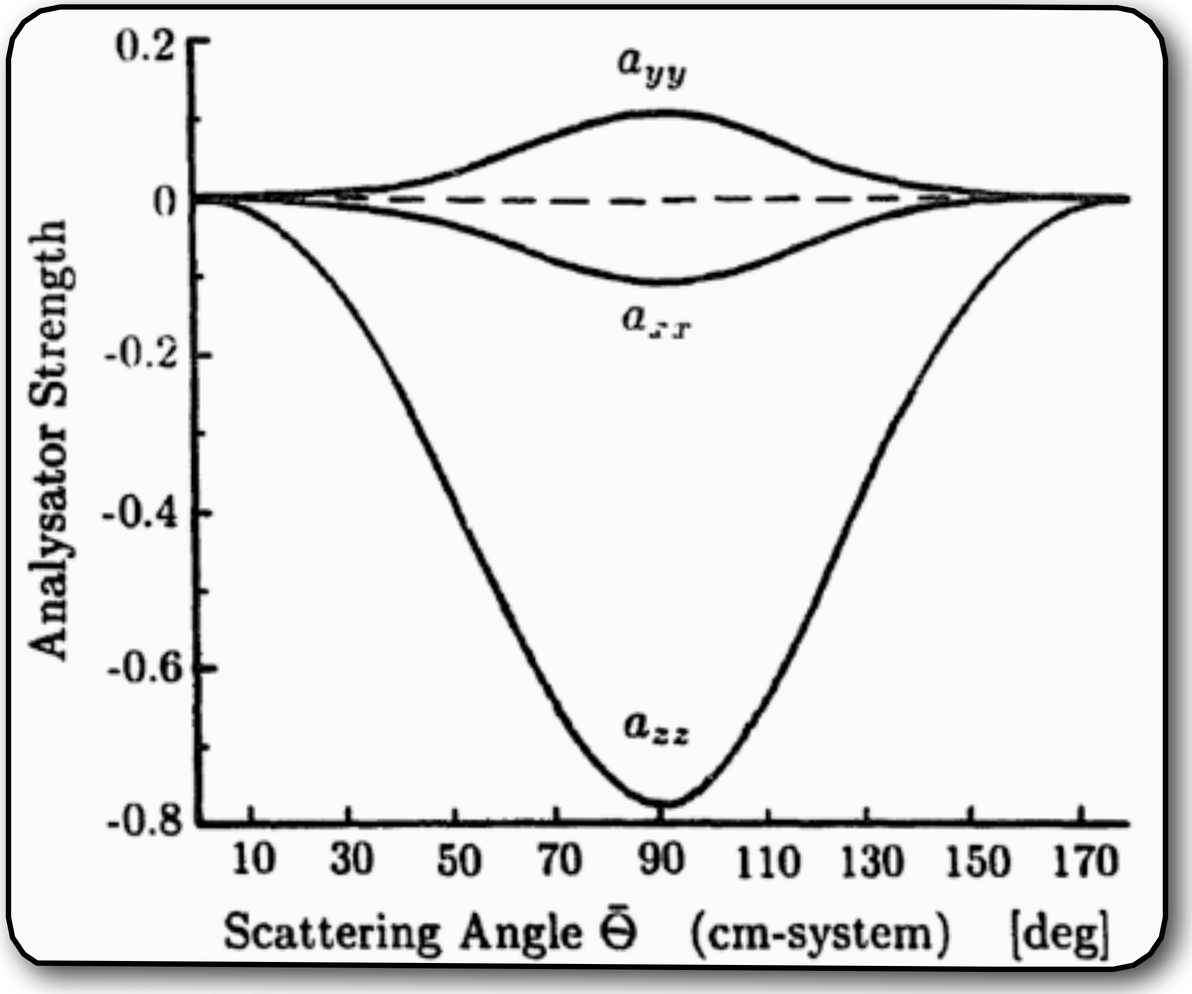
- small (0.1% - 5%) analyzing power
- rapid polarization measurement at low energies
- requires cross calibration with other polarimeters

**Used at MIT-Bates and Mainz for rapid, precise relative polarization measurements.**

# Møller Polarimeters

**Møller scattering:** $\vec{e} + \vec{e} \rightarrow e + e$ **target: Fe (or Fe- alloy) foils, polarized by external B field**

B. Wagner NIM A294, 541 (1990)



## Analyzing power:

exactly calculable in QED
independent of Energy
very large at $90^0$ CM angle
for longitudinally pol. electrons

## Target polarization:

low field along the plane
on Fe/Fe-alloy (large uncertainty)

very strong perpendicular field
on pure Fe foils, saturates
( smaller uncertainties)

**"work horse" for fixed target experiments, used from 100 MeV - 50 GeV**

**Rapid measurements, but, operates only at low currents and is invasive**

# Precision Møller Polarimetry

**L.G. Levchuk** (1992) - intrinsic momenta of the target electrons could have a significant affect on asymmetries measured in Møller polarimeters. Effect is largest in devices with very small acceptance or very high angular resolution.

**"Levchuk effect" makes some of the old results unreliable.**

**Newer polarimeters designed to minimize the uncertainty due to Levchuk effect**

**For example: The JLab Hall-C Møller polarimeter**

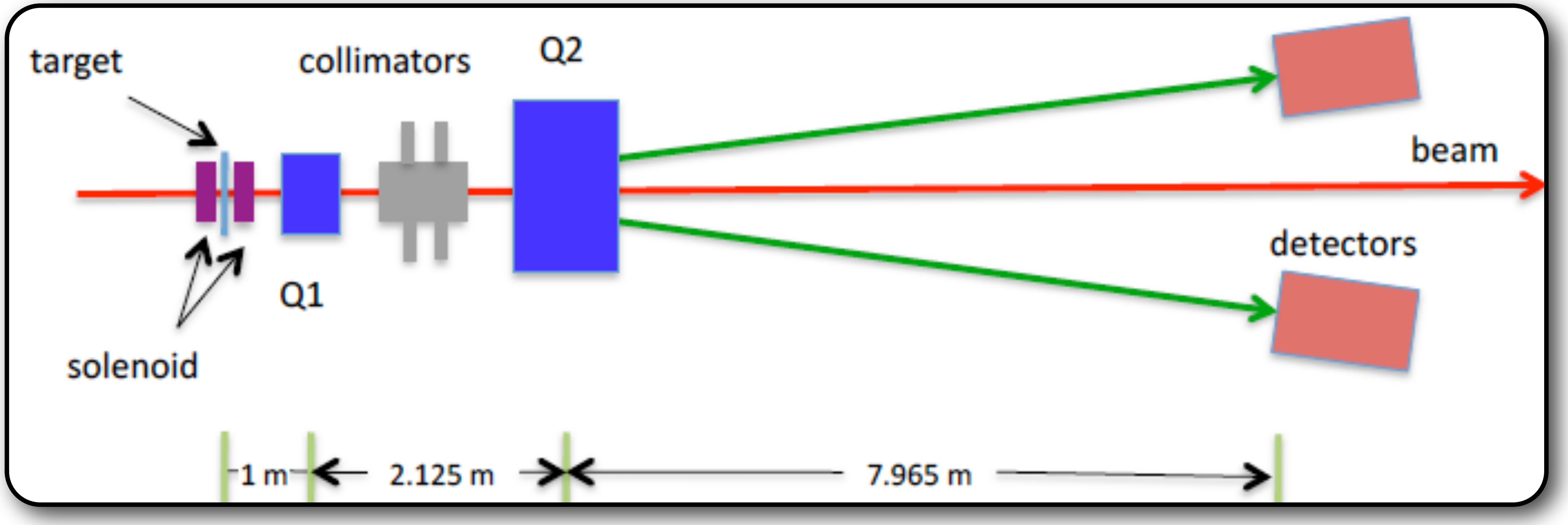
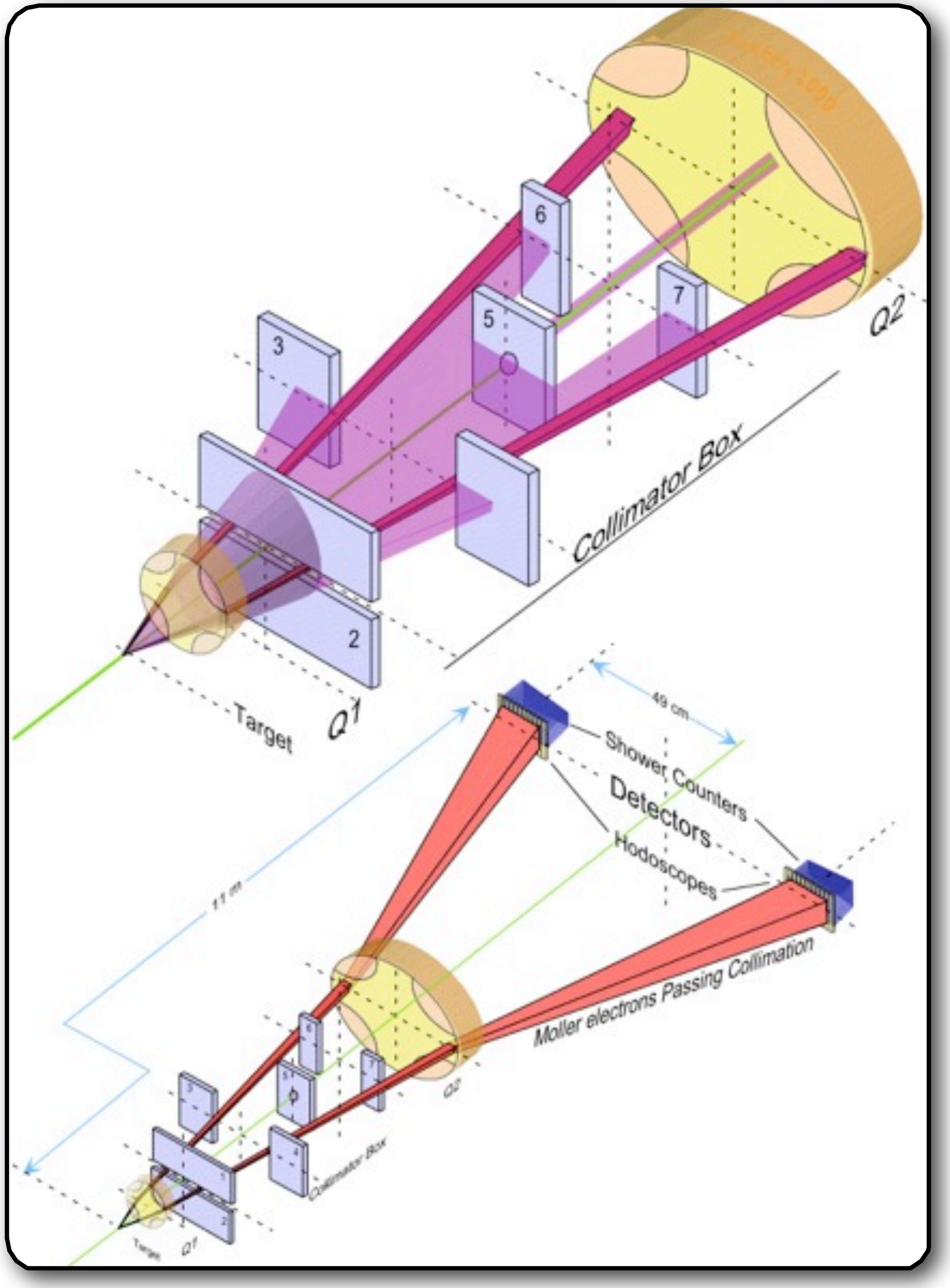


**Figure: Courtesy of D. Gaskell (JLab)**

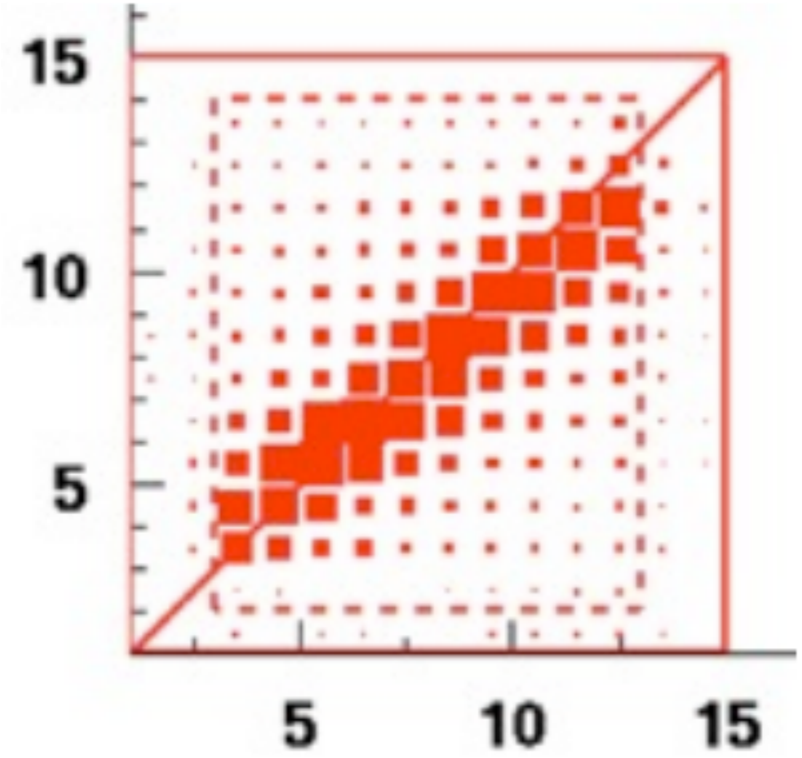
- moderate acceptance minimizes Levchuk effect (still a non-trivial contribution)
- pure Fe foil with 3-4 T superconducting magnet
- 0.25% target polarization uncertainty (**NIM A462, (2001) 382**)

# Precision Møller Polarimetry

## The JLab Hall-C Møller polarimeter



- 2 quadrupole design maintains constant tune at detector plane (energy independent acceptance)
- collimation and coincidence detection provides clean signal



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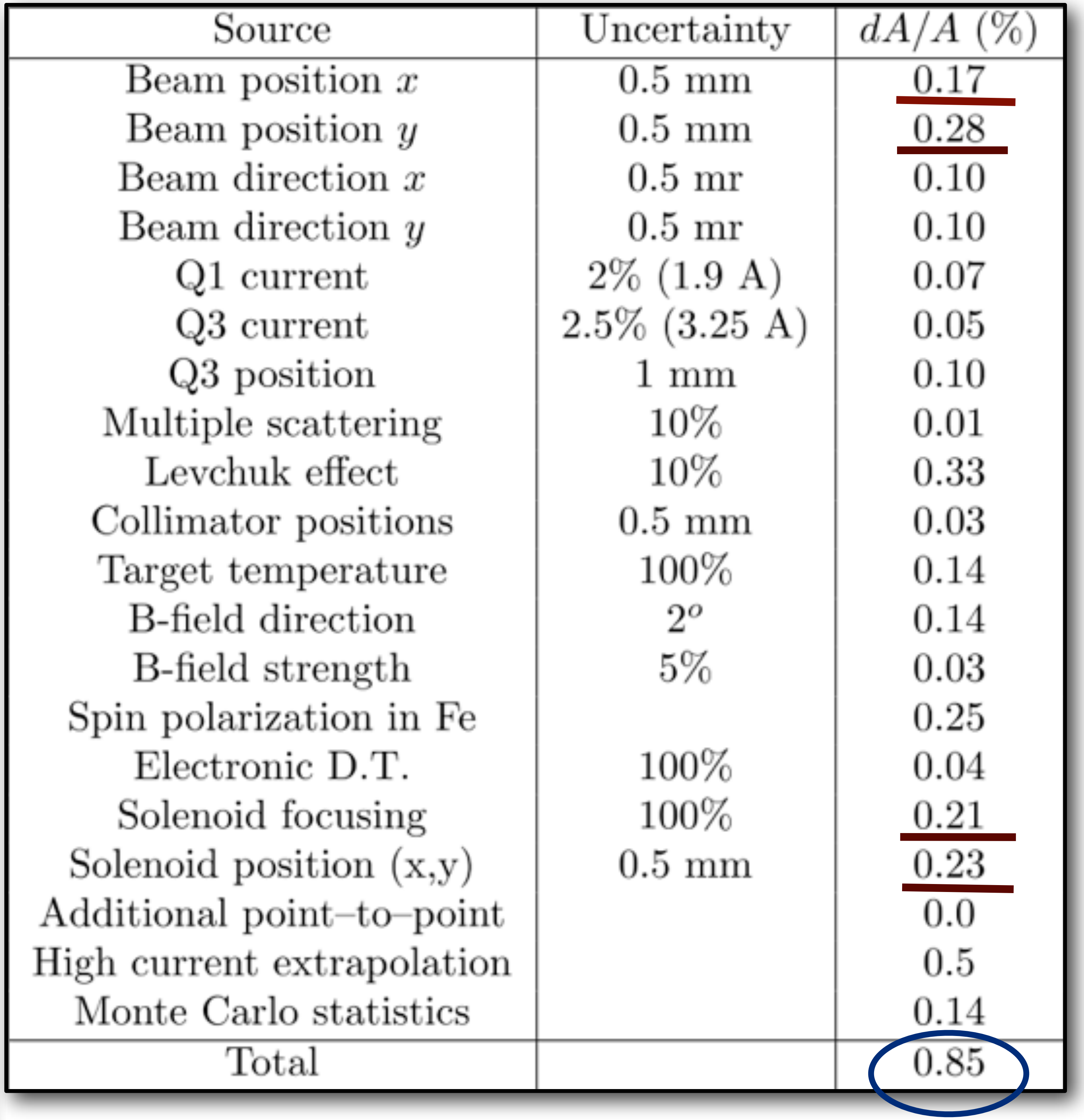
# Precision Møller Polarimetry

## Hall-C Møller systematic uncertainties (for QWeak run-2)



| Source | Uncertainty | $dA/A$ (%) |
|---|---|---|
| Beam position $x$ | 0.5 mm | 0.17 |
| Beam position $y$ | 0.5 mm | 0.28 |
| Beam direction $x$ | 0.5 mr | 0.10 |
| Beam direction $y$ | 0.5 mr | 0.10 |
| Q1 current | 2% (1.9 A) | 0.07 |
| Q3 current | 2.5% (3.25 A) | 0.05 |
| Q3 position | 1 mm | 0.10 |
| Multiple scattering | 10% | 0.01 |
| Levchuk effect | 10% | 0.33 |
| Collimator positions | 0.5 mm | 0.03 |
| Target temperature | 100% | 0.14 |
| B-field direction | $2^o$ | 0.14 |
| B-field strength | 5% | 0.03 |
| Spin polarization in Fe |  | 0.25 |
| Electronic D.T. | 100% | 0.04 |
| Solenoid focusing | 100% | 0.21 |
| Solenoid position (x,y) | 0.5 mm | 0.23 |
| Additional point–to–point |  | 0.0 |
| High current extrapolation |  | 0.5 |
| Monte Carlo statistics |  | 0.14 |
| Total |  | 0.85 |

Table courtesy of D. Gaskell (JLab)

**Some uncertainties larger because of the low energy (1 GeV) operation during QWeak**

**total uncertainty < 1% for the recent QWeak experiment.**

**At higher energies the total uncertainty is expected to be ~0.45%**

**Only issues:**
works only at low currents,
invasive to the experiment

# Compton Polarimeters

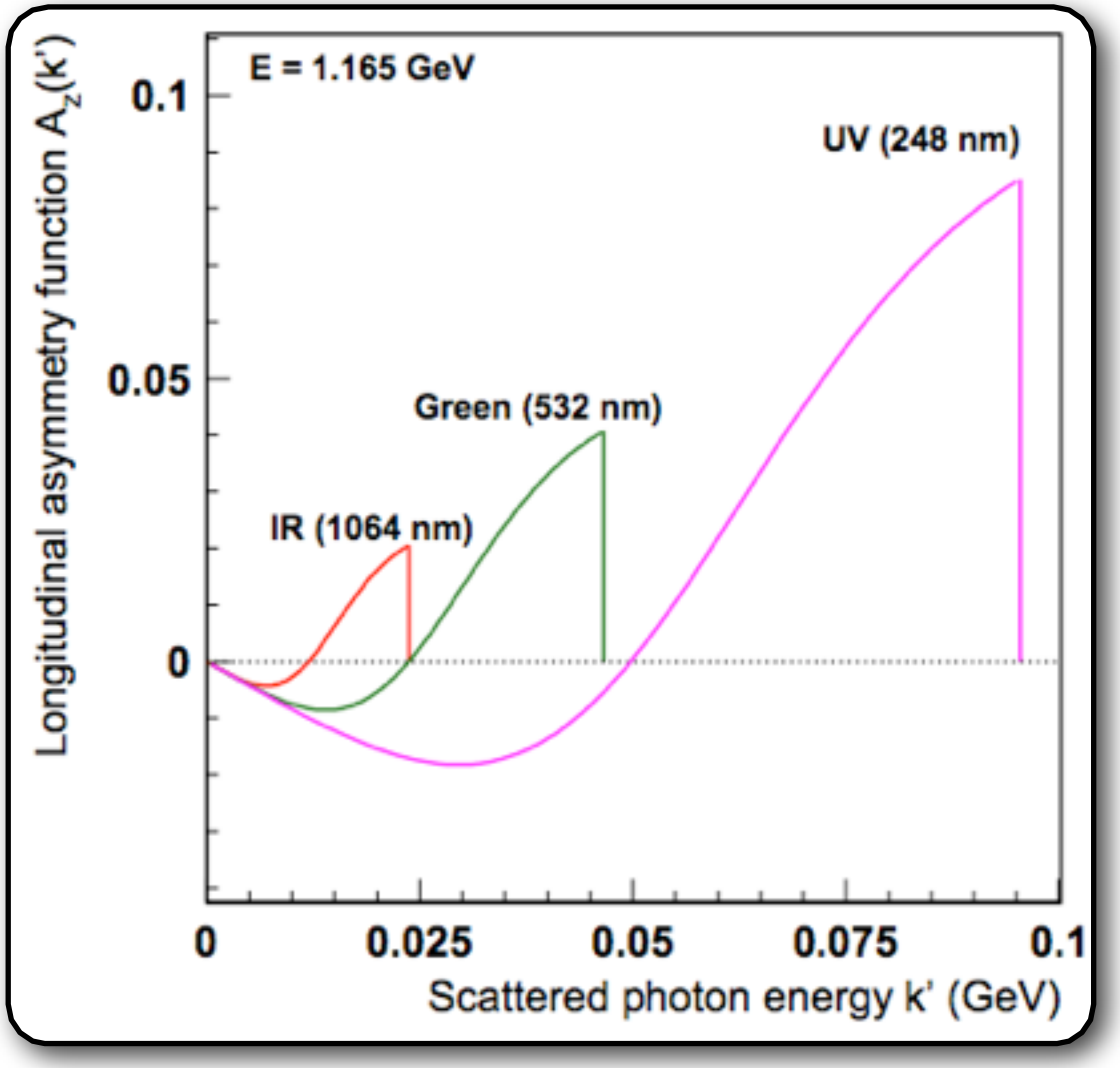
$$\vec{e} + \vec{\gamma} \rightarrow e + \gamma$$

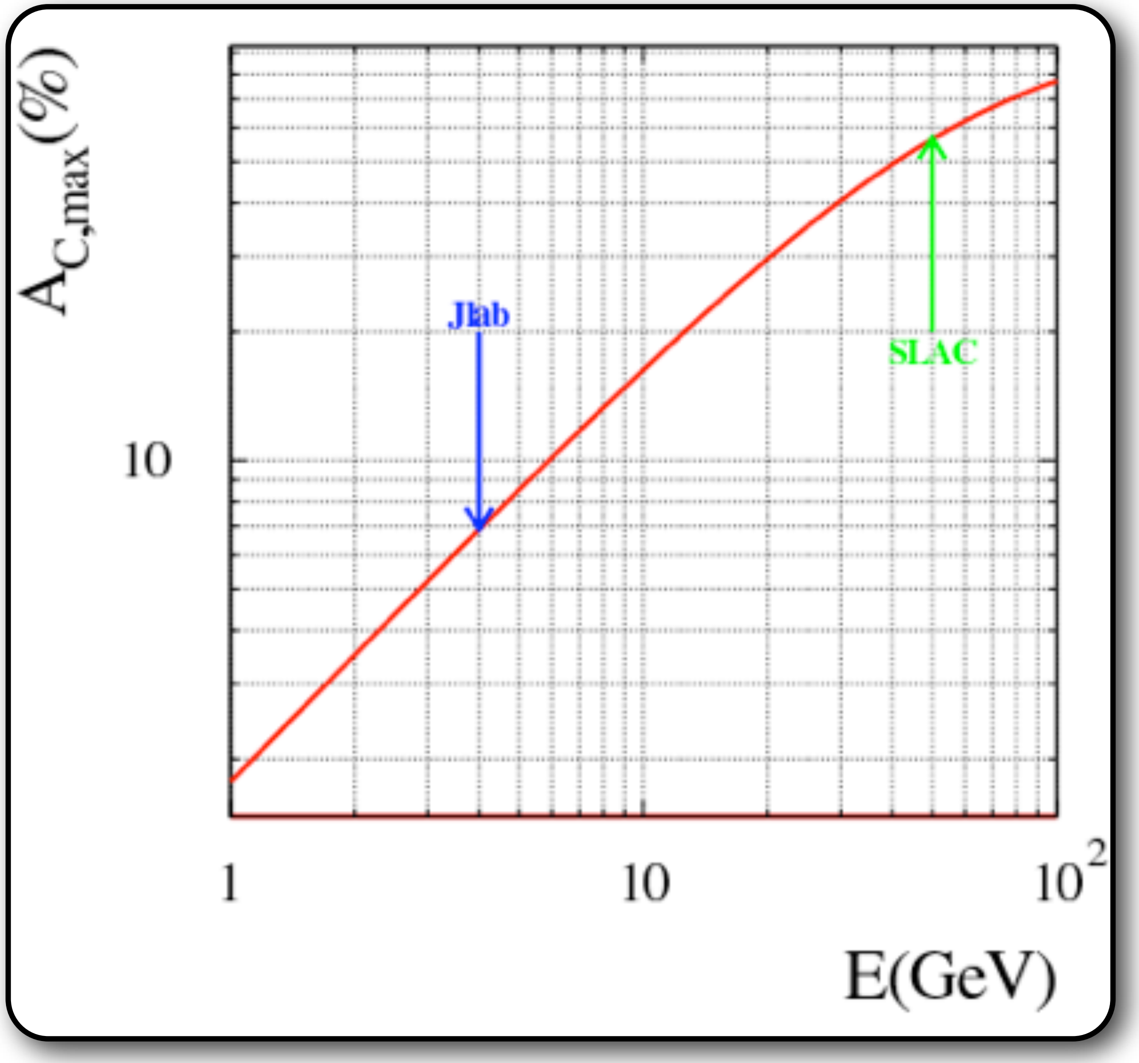
$$\frac{\sigma_{\uparrow\uparrow}-\sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow}+\sigma_{\uparrow\downarrow}} = A_z \cdot \mathcal{P}_e \cdot \mathcal{P}_\gamma$$

**QED** **~100%**

**Exploits the spin - dependence of the polarized electron - photon scattering cross section.**

**Longitudinal asymmetry increases with photon and electron energy**





Transverse polarization can be measured from the azimuthal angle dependence of the asymmetry (as an up-down asymmetry).

# Compton Polarimeters

$$\vec{e} + \vec{\gamma} \rightarrow e + \gamma$$

**Exploits the spin - dependence of the polarized electron - photon scattering cross section.**

$$\frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}} = \underset{\substack{\uparrow \\ \text{QED}}}{A_z} \cdot \mathcal{P}_e \cdot \underset{\substack{\uparrow \\ \sim 100\%}}{\mathcal{P}_\gamma}$$

- **Analyzing power strongly energy dependent:** detector thresholds and non-linearities can be an issue for photon detector
- **Small asymmetry at low energies** (expect lower precision at low energies)

- **Negligible theoretical error:** higher order corrections < 0.1% at 1 GeV increases slowly with energy (NPB 540 (1999) 58)

- **Rapid:** $T \propto 1/(k^2E^2)$, **non-invasive polarimeter**
- **2-in-1 polarimeter:** electron and photon provide independent measurements
  - scattered electrons very close to beam at low energies
  - photon detection requires knowledge of resolution function

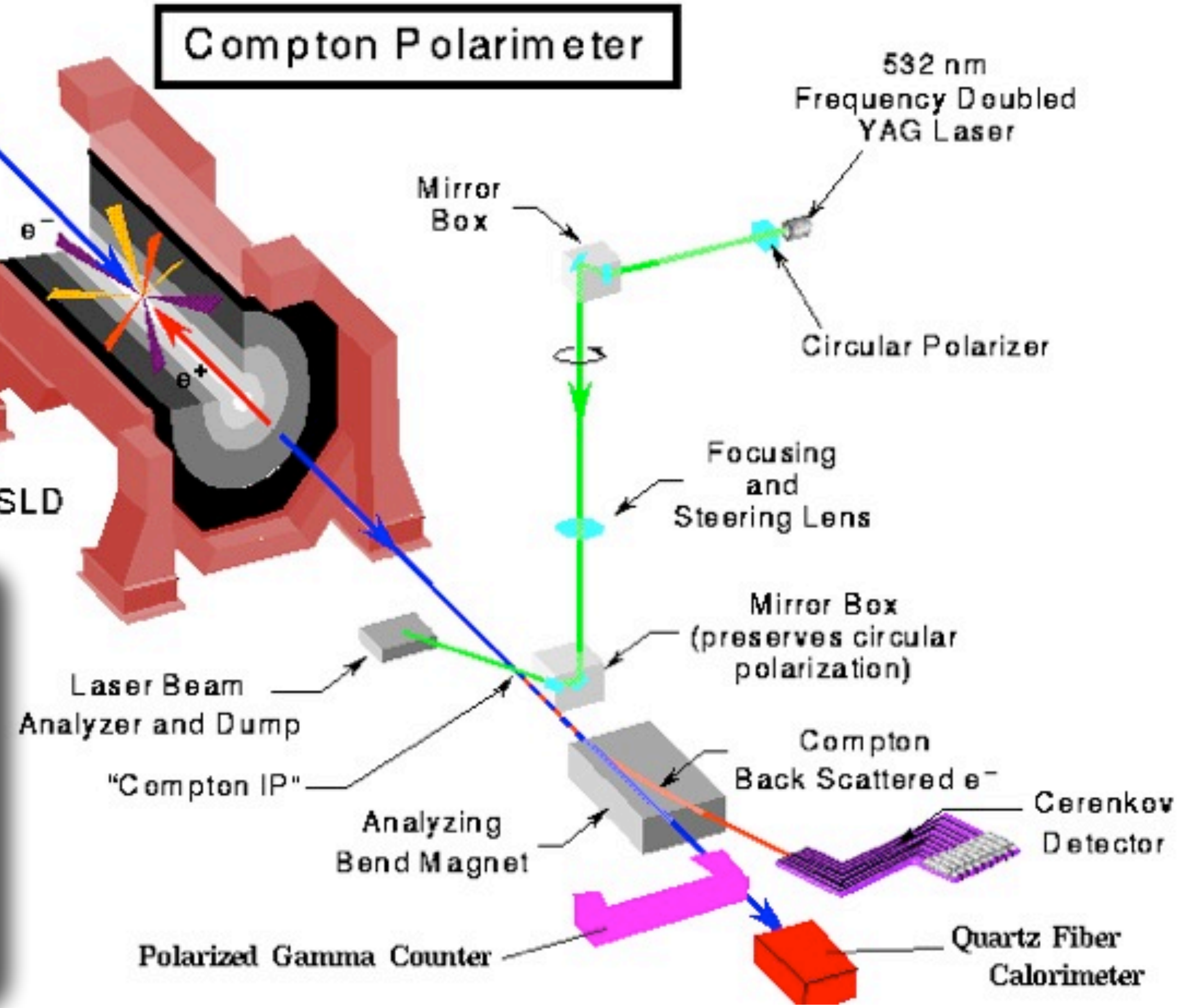
**Compton polarimeters - used over a wide range of energies (800 MeV - 50 GeV) and a variety of accelerators - SLAC, HERA, LEP, NIKHEF, MIT-Bates & JLab**

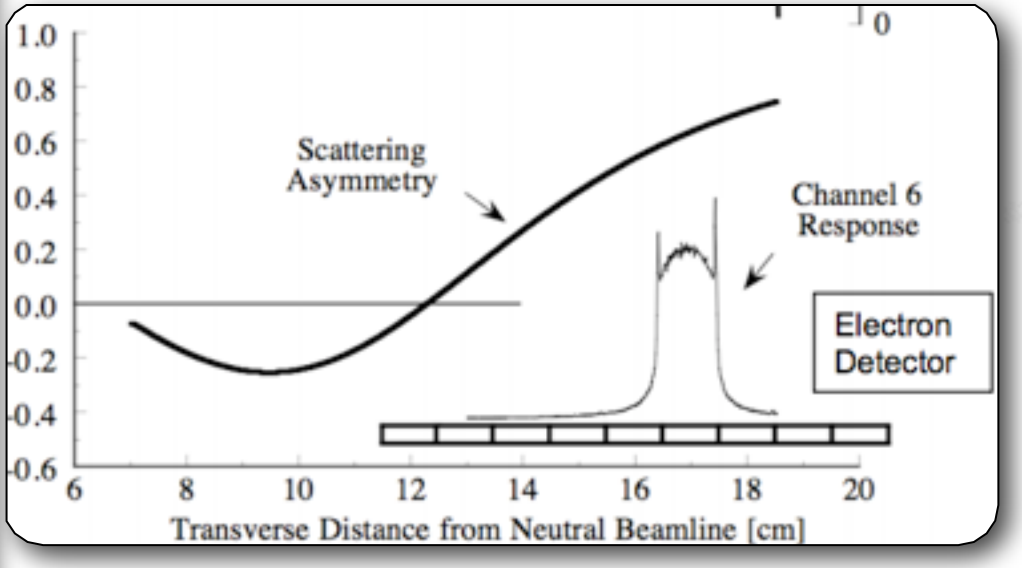
# SLD Compton Polarimeter

**Integrating electron and photon detectors**

**δP/P = 0.5%,**
**best reported precision**
**of all Compton polarimeters**

**(Ann. Rev. Nuc. Part. Sci. 51, (2001) 345)**

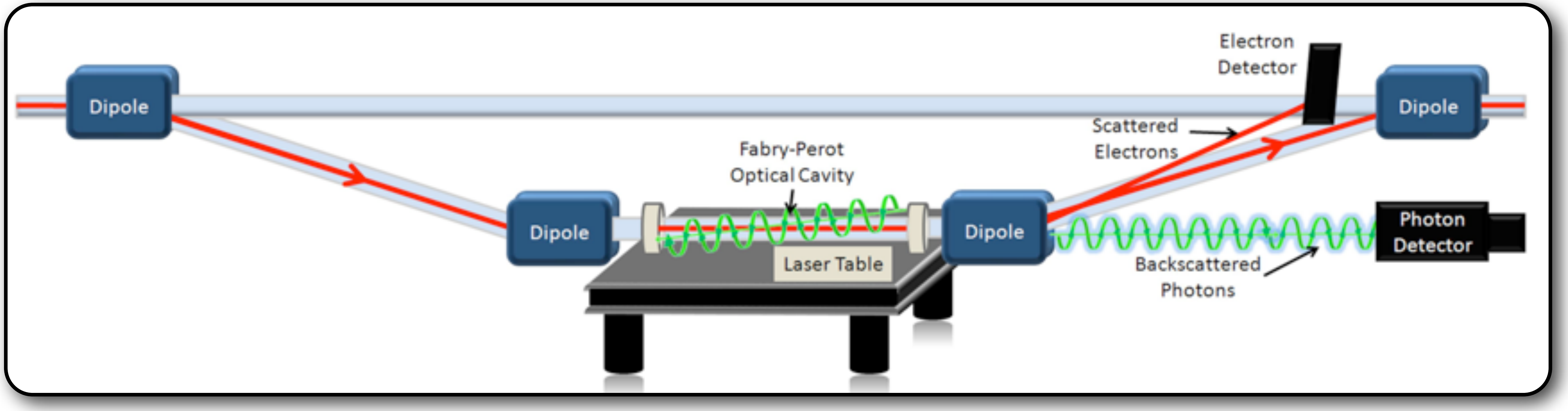




**Conventional wisdom:** high precision Compton polarimetry limited to very high energies.

# JLab Compton Polarimeters

## Halls A and C have similar Compton Polarimeters



**4-dipole chicane:** deflect beam vertically

**Laser system:** Fabry-Perot cavity pumped by CW laser (green 532 nm), few kW of stored laser power

**Photon detector:** PbWO4 or GSO - operated in integrating mode
**Electron detector:** micro-strip detector

**Bucking conventional wisdom, in recent years, JLab Compton polarimeters have demonstrated sub-1% uncertainty at low energies**

# Some Recent Results

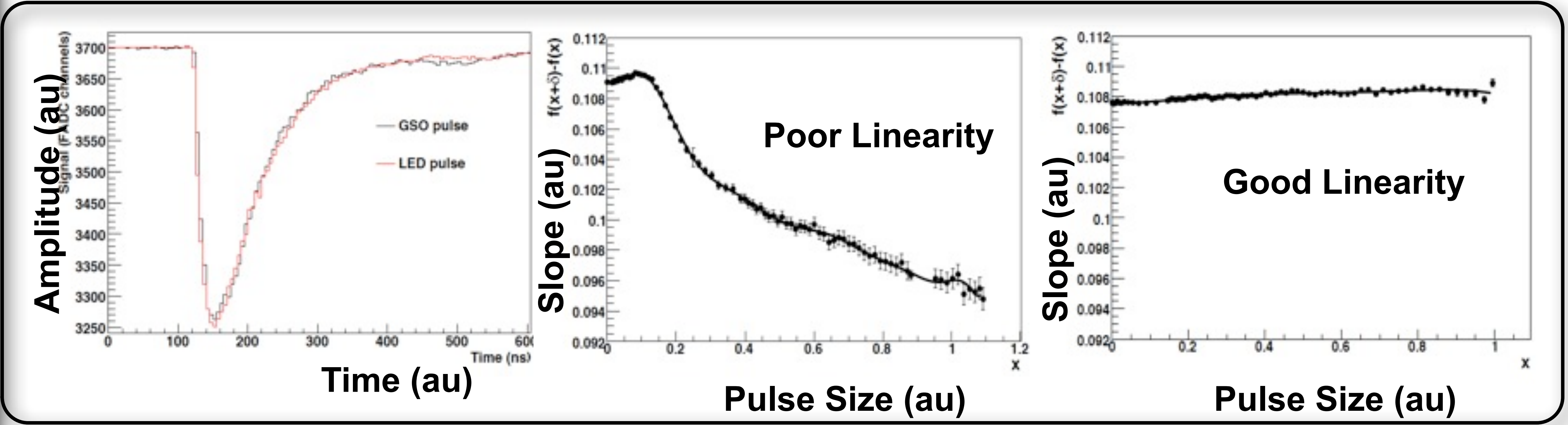
## Hall A Compton Photon Calorimeter results

**New GSO detector and Energy weighted asymmetry** (led by Carnegie Mellon)

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

Energy weighted asymmetry ⇒

**no threshold** (analyzing power well understood)
**less sensitive** to knowledge of resolution function
**Challenge:** understanding detector non-linearities
(used an LED pulser system to study non-linearities)



D. Gaskell (PaVi14) and G. Franklin (EIC14)

# Some Recent Results

## Hall A Compton Photon Calorimeter results

**New GSO detector and Energy weighted asymmetry** (led by Carnegie Mellon)

Photon detector systematic uncertainties

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

| 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% |

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

**Excluding laser polarization, total uncertainty < 0.5%**

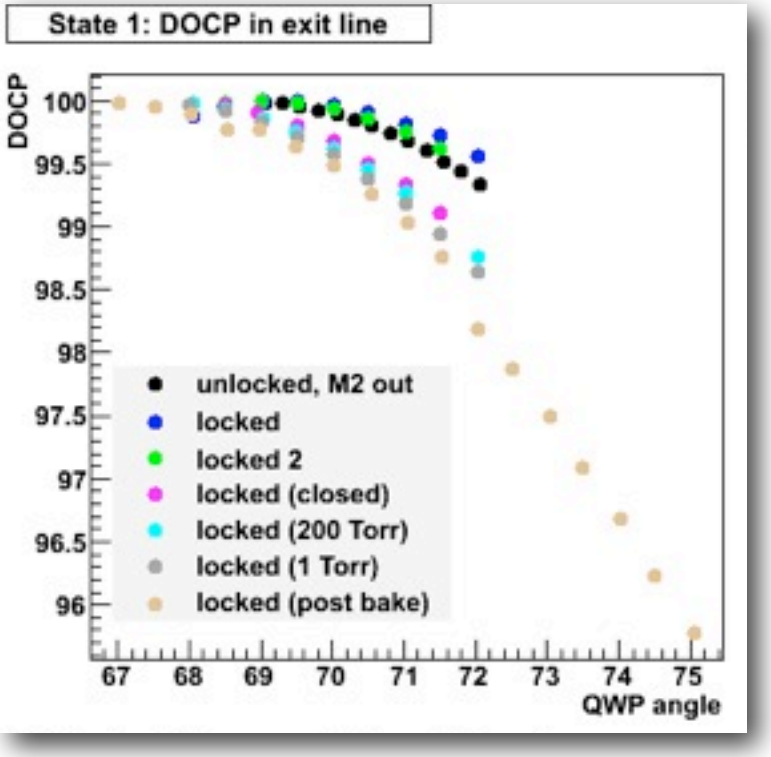
**D. Gaskell (PaVi14) and G. Franklin (EIC14)**

# Some Recent Results

## Hall C Compton results (Determining laser polarization)

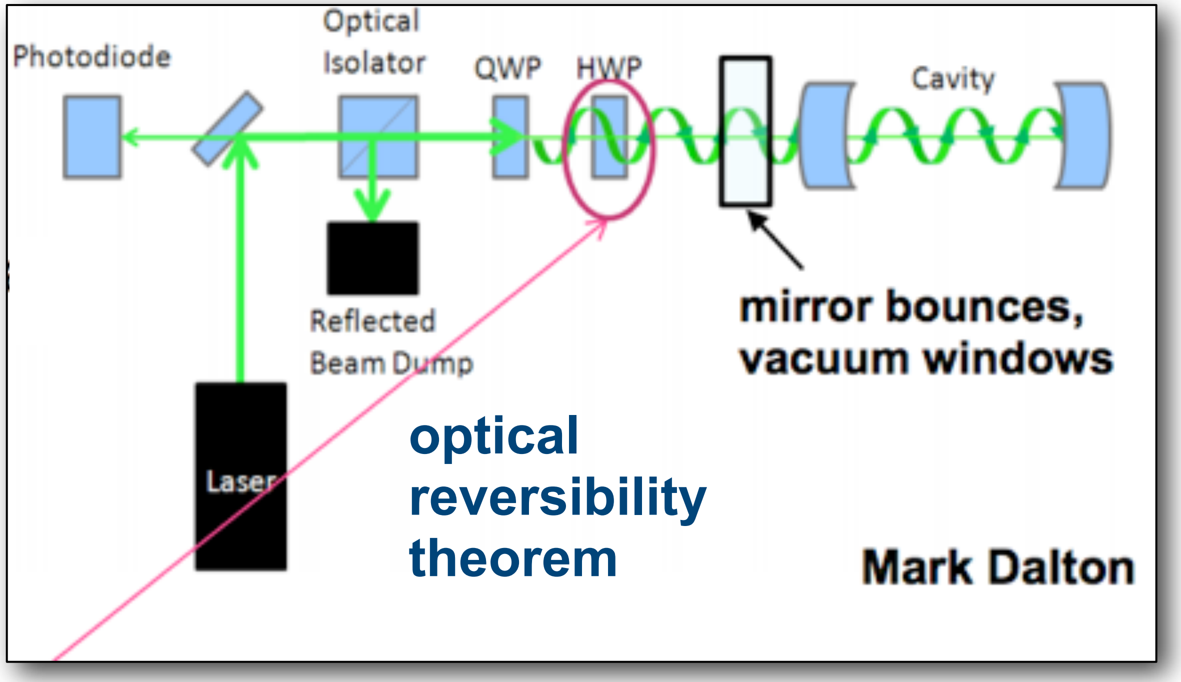
### Polarization inside cavity monitored using transmitted or reflected light

**Transfer function** translates polarization of transmitted light to polarization in the cavity


State 1: DOCP in exit line

Possible complications:
- vacuum stress
- heating
- alignment variations

**Optical isolation** through use of beam polarization, this isolation fails to the degree that light is not perfectly circular at the reflecting surface



**mirror bounces, vacuum windows**

**optical reversibility theorem**

**Mark Dalton**

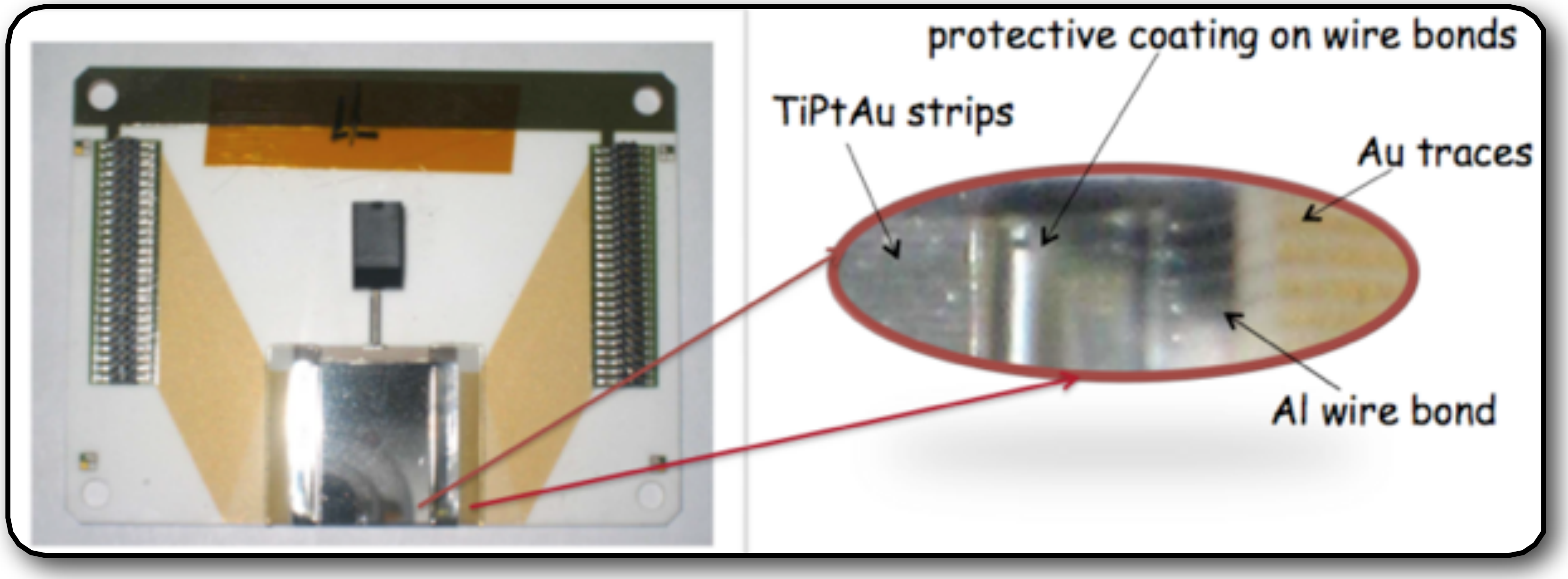
Provides a means to remotely maximize circular polarization in-situ. DOCP controlled at the 0.1% level.

**Overall systematic error on laser polarization in cavity ~ 0.1%**

**D. Gaskell (PaVi14) & K. Paschke (PSTP 13)**

# Some Recent Results

## Hall C Compton Electron Detector



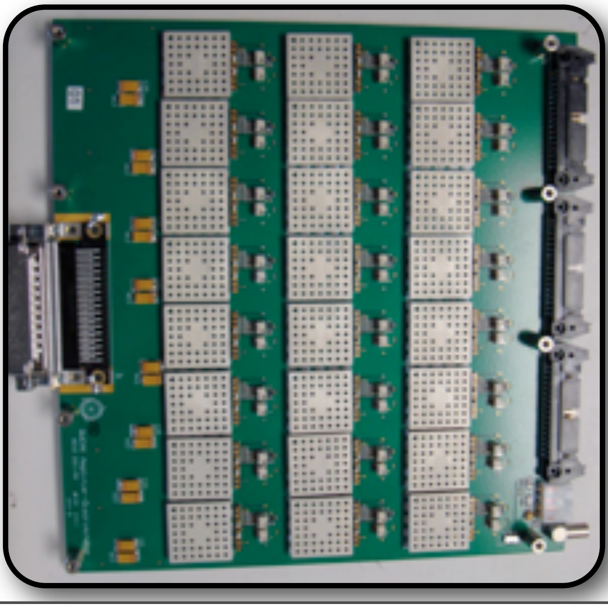
**First use of diamond micro-strip detector as a tracking detector**

**desirable for its radiation hardness**
**bonus:** insensitive to synchrotron radiation

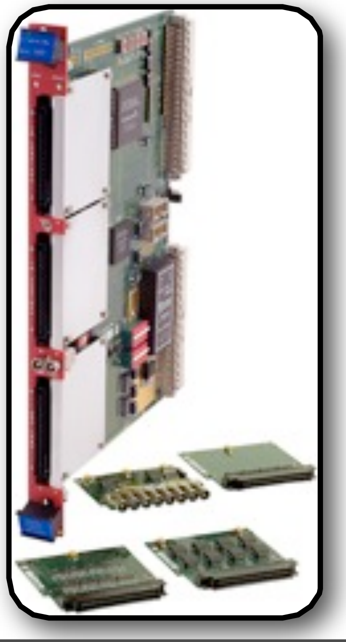
### Other key elements

**low capacitance, 6 layer, flexible cable (KADFLX Inc)**

**QWAD QWeak Amplifier Discriminator low noise pre-amplifier, shaper and discriminator chain, built by TRIUMF**



**FPGA based pipeline DAQ**



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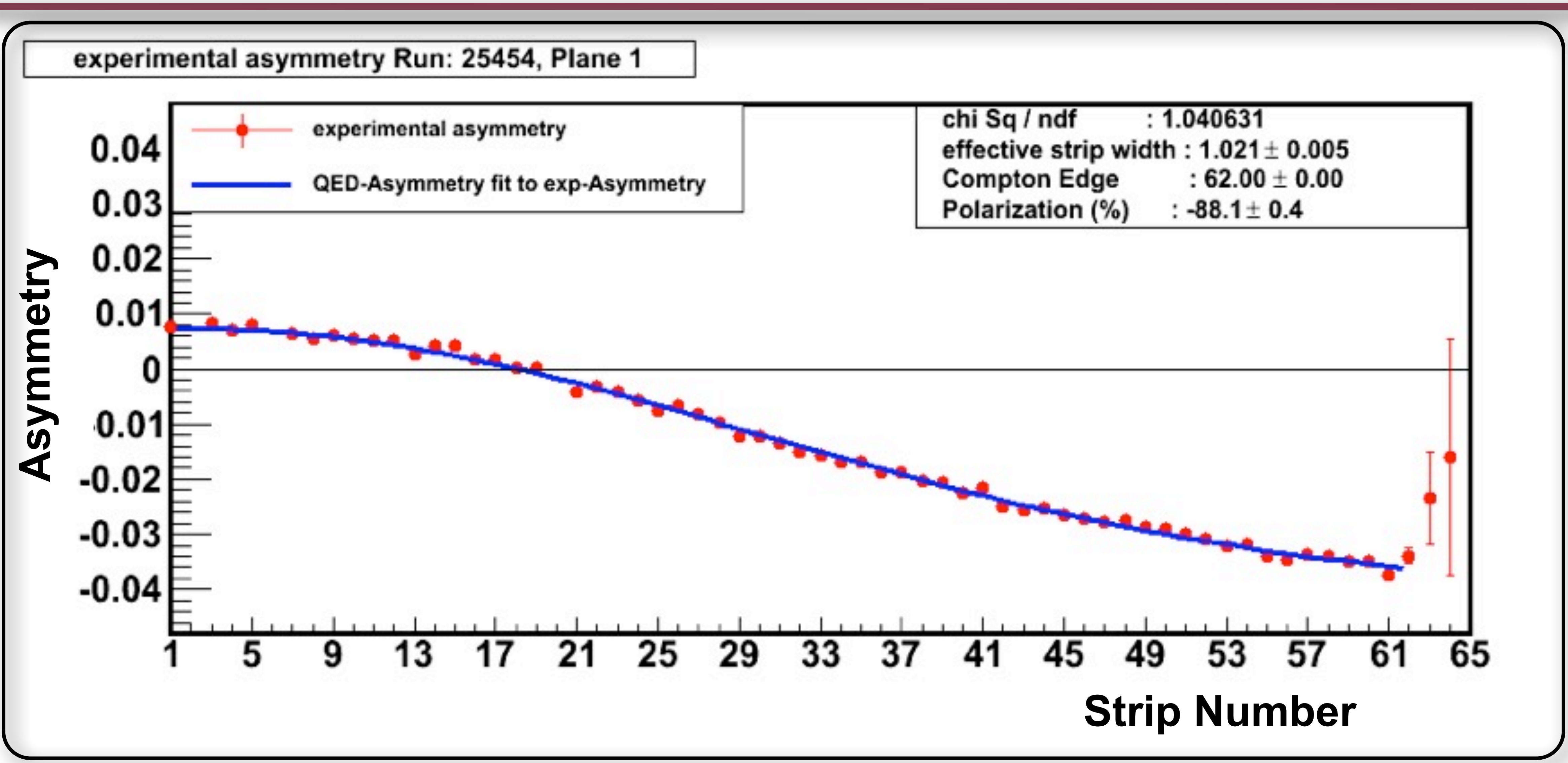
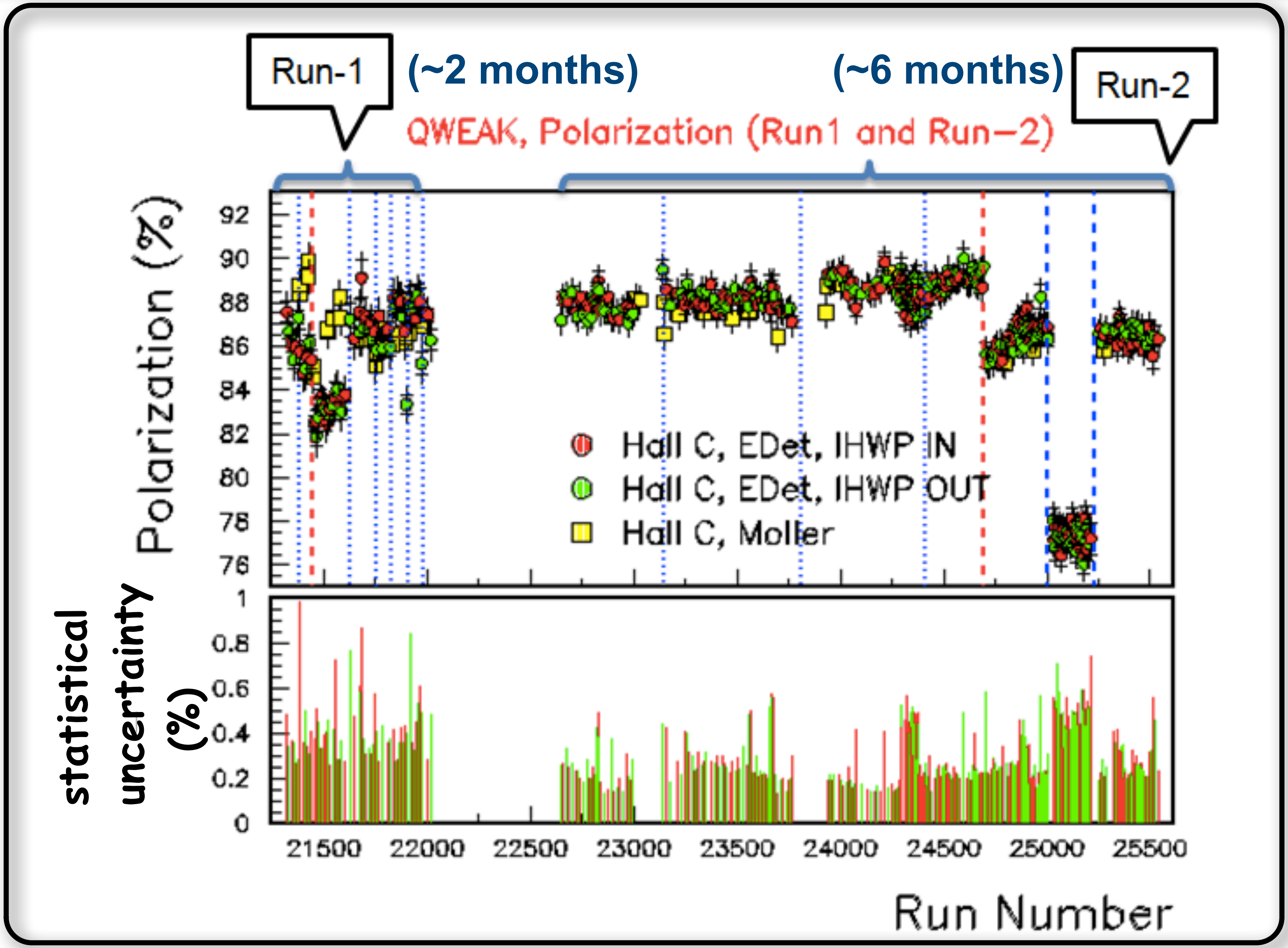
# Electron Detector Results



**2 parameter fit (polarization and Compton edge) to the asymmetry spectrum. results show that:**

- ★ **Strip width (resolution) is important**
- ★ **Zero-crossing must be in acceptance to constrain the fit well**

# Electron Detector Results



**Electron detector was used all thorough the QWeak experiment for continuous, non-invasive monitoring of polarization at full beam current.**

# Electron Detector Results

## Preliminary Systematic Uncertainties

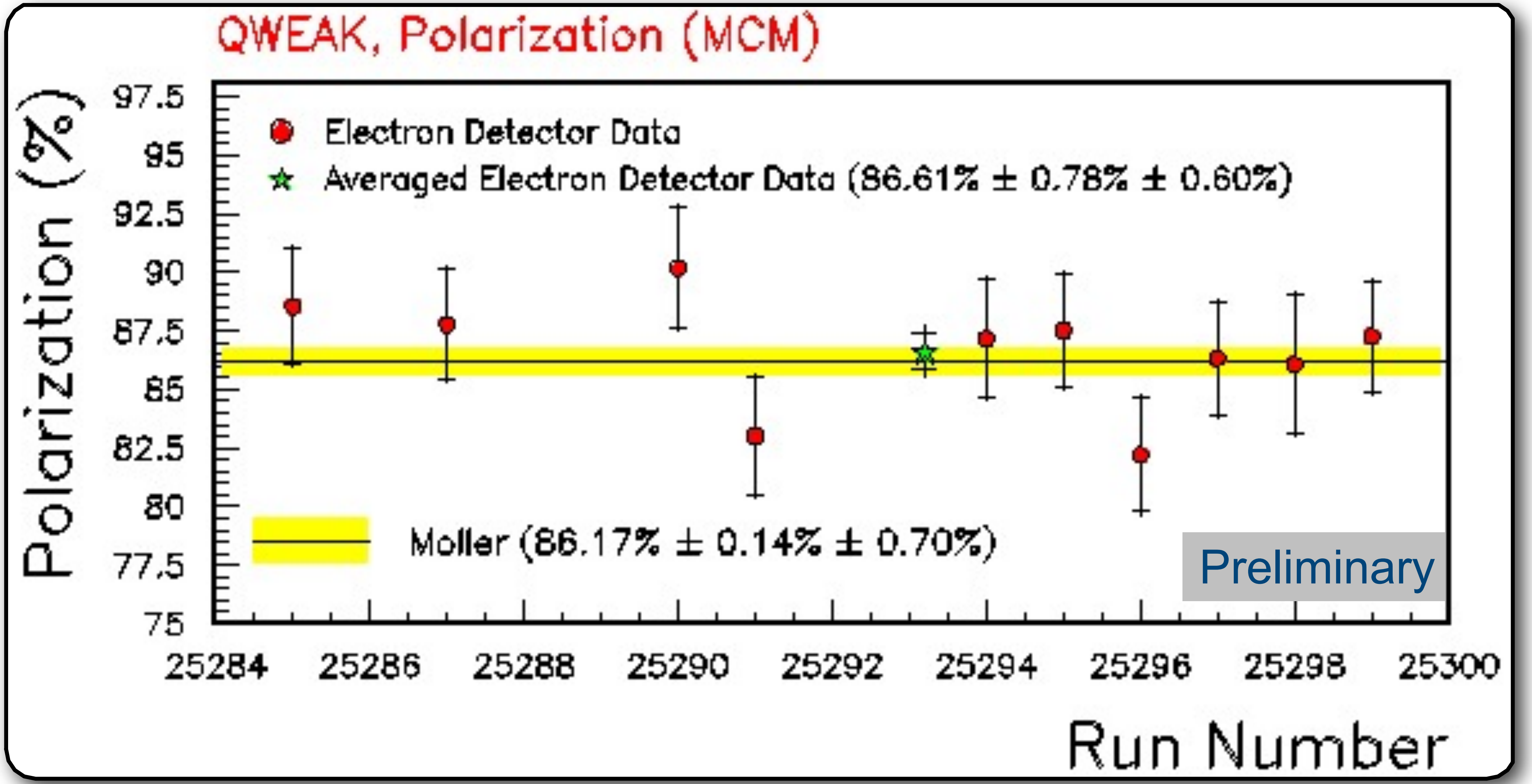
| Systematic Uncertainty | Uncertainty | ΔP/P (%) |
|---|---|---|
| Laser Polarization | 0.2% | 0.2 |
| Dipole field strength | (0.0011 T) | 0.02 |
| Beam energy | 1 MeV | 0.09 |
| Detector Longitudinal Position | 1 mm | 0.03 |
| Detector Rotation (pitch) | 1 degree | 0.04 |
| Asymmetry time averaging | 0.15% | 0.15 |
| Secondaries (trigger) | - | 0.18 |
| DAQ – dead time, eff. | - | 0.5* |
| Other | ? | - |
| Total | | 0.60* |

“Other” systematic uncertainties still under investigation, but final precision expected to be **better than 1%**

★ DAQ- related systematics come from combination of complicated trigger, and variation of strip efficiency: can be reduced if simpler trigger can be used

# Møller - Compton Cross Calibration

During QWeak experiment: **Møller** measurement @ **1 μA**
**Compton** measurement @ **180 μA**



## Cross calibration @ 4.5 μA

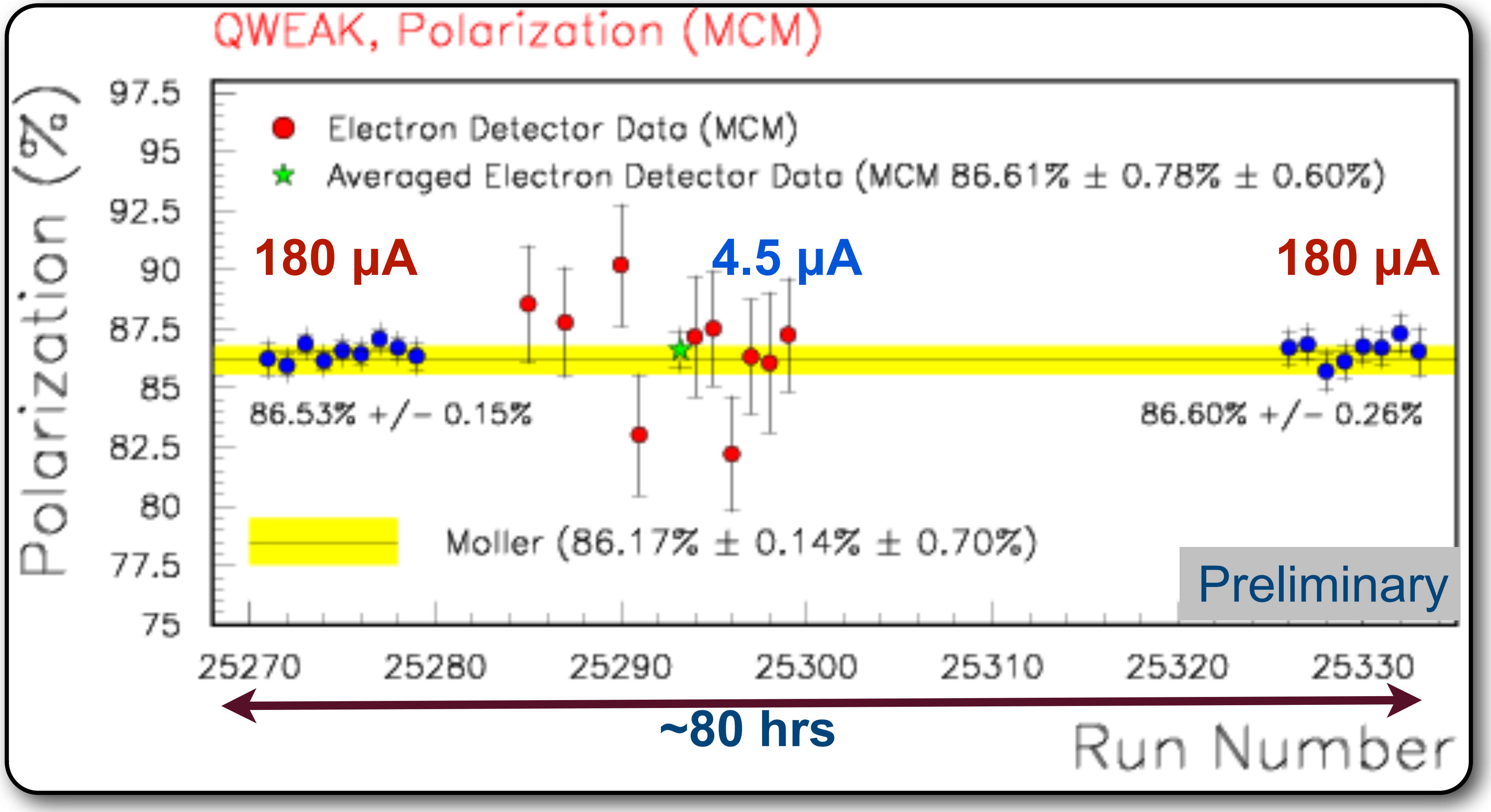
**Compton:** smaller signal to noise ⇒ larger sensitivity to noise

**Møller:** extra corrections for beam heating and dead time corrections

**Excellent agreement**

# Møller - Compton Cross Calibration

**Looking for beam current dependence of polarization**



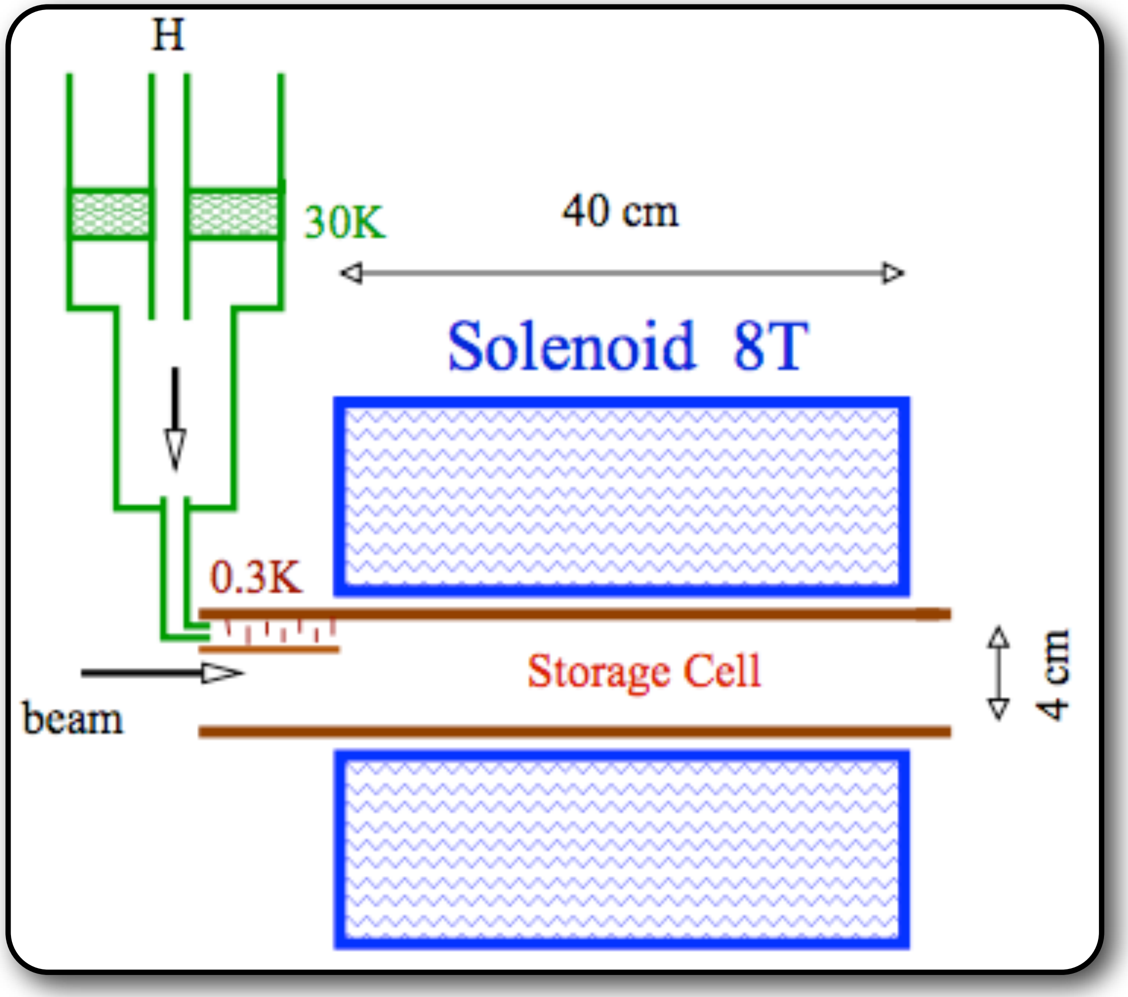
**Compare low current Compton & Møller with high current Compton immediately before and after the cross calibration.**

**No beam current dependence found**

# Future Possibilities

## Atomic Hydrogen Møller Polarimeter

E. Chudakov and V. Luppov IEEE Trans. on Nucl. Sc., 51, 1533 (2004)



- 100% target polarization
- negligible error on target polarization
- no Levchuk effect
- thin target ⇒ no dead time
  but sufficient rates for 1%
  stat. in 10 min @ 100 μA
- non-invasive, continuous
  hight current measurement
- technically challenging

Brute force polarization of atomic H
with 8T field and 300 mK temperature
density ~ $6 \times 10^{16}$ H/cc

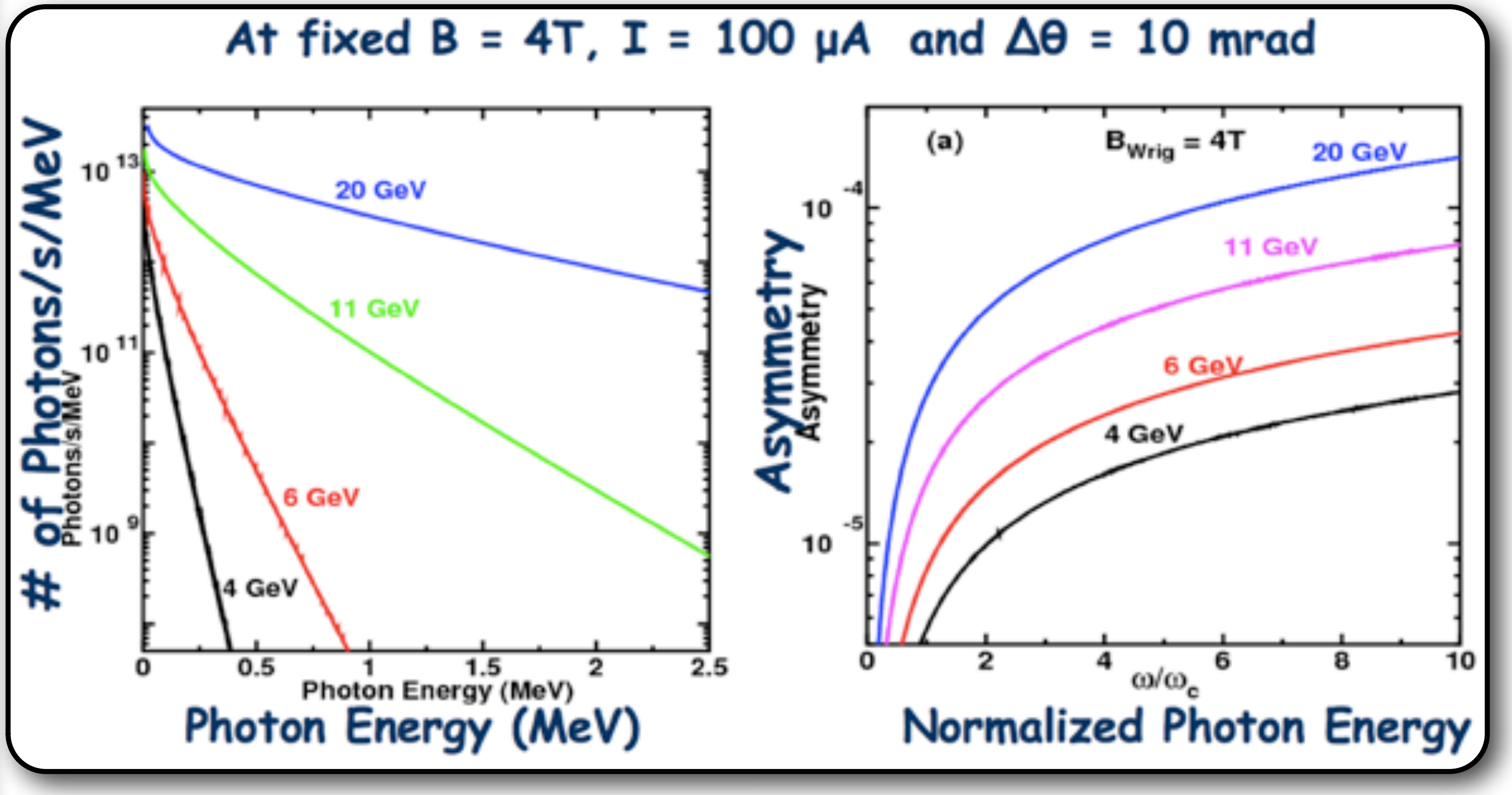
R&D underway at Mainz and W&M

# Future Possibilities

## Spin-light Polarimeter

P. Mohanmurthy and D. Dutta, IEEE Trans. on Nucl. Sc., 61, 528 (2014)

**Exploit the spatial asymmetry of synchrotron radiation emitted by longitudinally polarized electrons in a magnetic field.**



- continuous, non-invasive, rapid polarimetry
- small energy dependent asymmetry
- needs position sensitive x-ray detector
- differential detector to mitigate beam motion related false asymmetry
- large SR load on beamline
- several technical challenges

**relative longitudinal polarimetry may be feasible**

**Transverse polarimetry much less challenging**

verified at the VEPP-4 storage ring; **Belomesthnykh et al., NIM 227, 173 (1984)**

**R&D and simulations underway**

# Summary

- Precision electron polarimetry has been at the forefront of a large physics program that ranges from nucleon structure to searches for new physics.
- A complementary set of polarimetry techniques have been developed such as Mott, Møller and Compton.
- All of these methods are being pushed to ever higher precision.
- The only way to achieve the desired higher precision in the upcoming physics program is to use multiple methods simultaneously.
- A few new alternative methods have also been proposed and R&D is ongoing to demonstrate their feasibility.