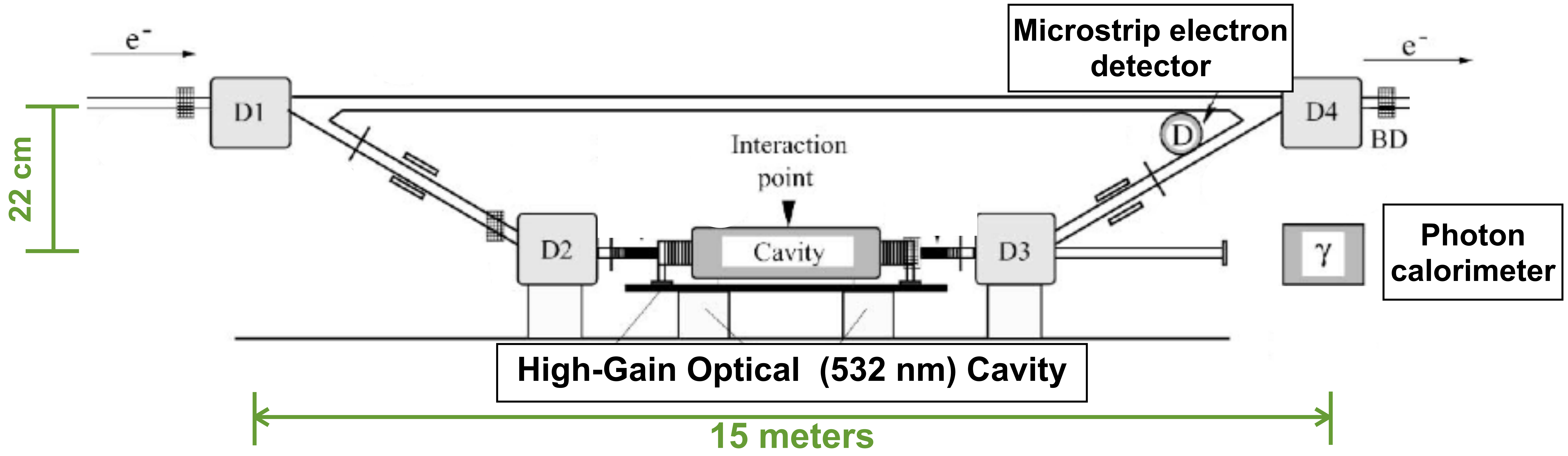
# Polarization Extraction with the Compton Polarimeter

Kent Paschke

# Compton Polarimetry in Hall A

- Polarized electron-photon scattering
- Independent detection of backscattered photons and recoil electrons
- state-of-the-art: 0.4% precision at JLAB at 1 GeV

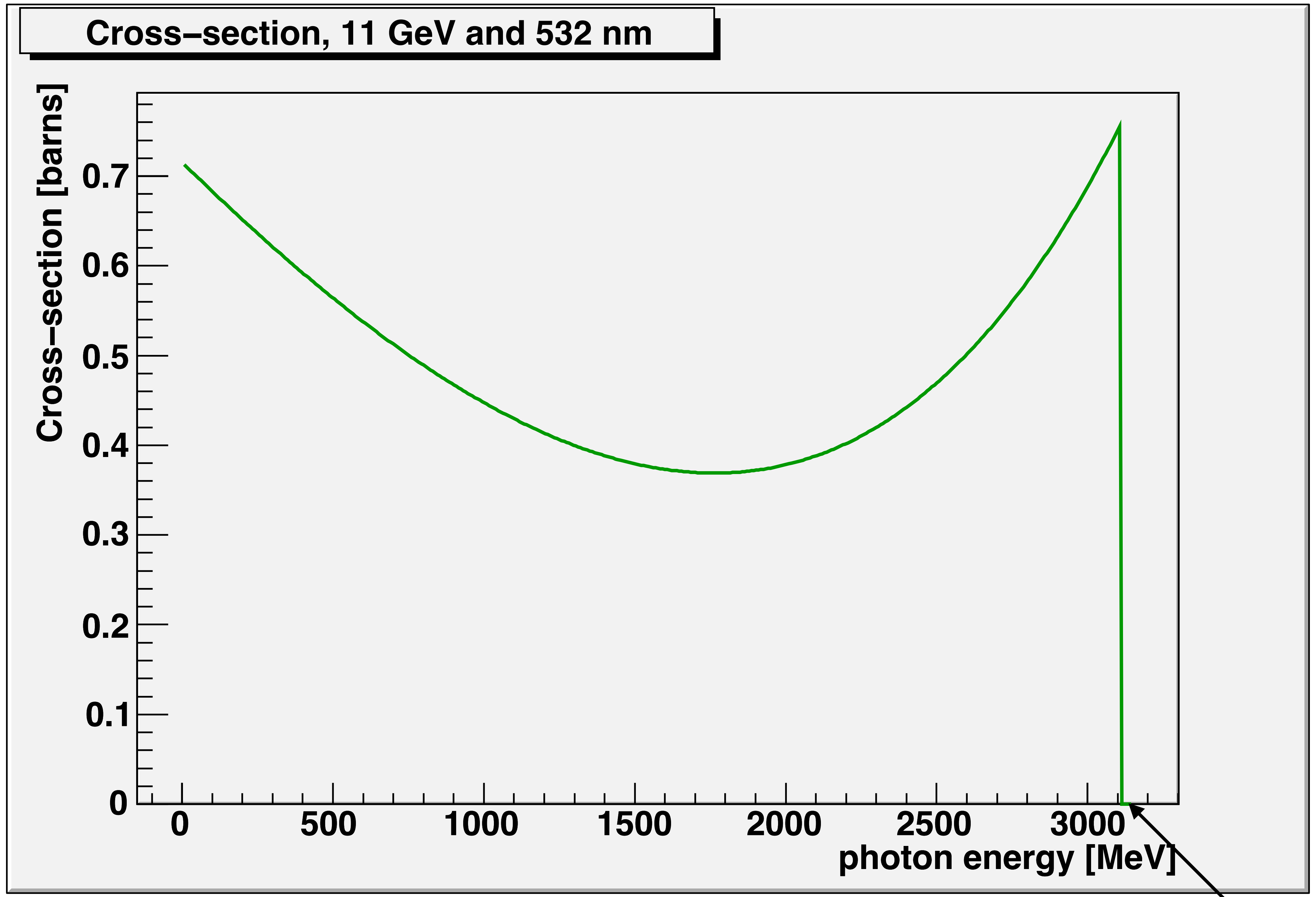


Microstrip electron detector

Photon calorimeter

High-Gain Optical (532 nm) Cavity

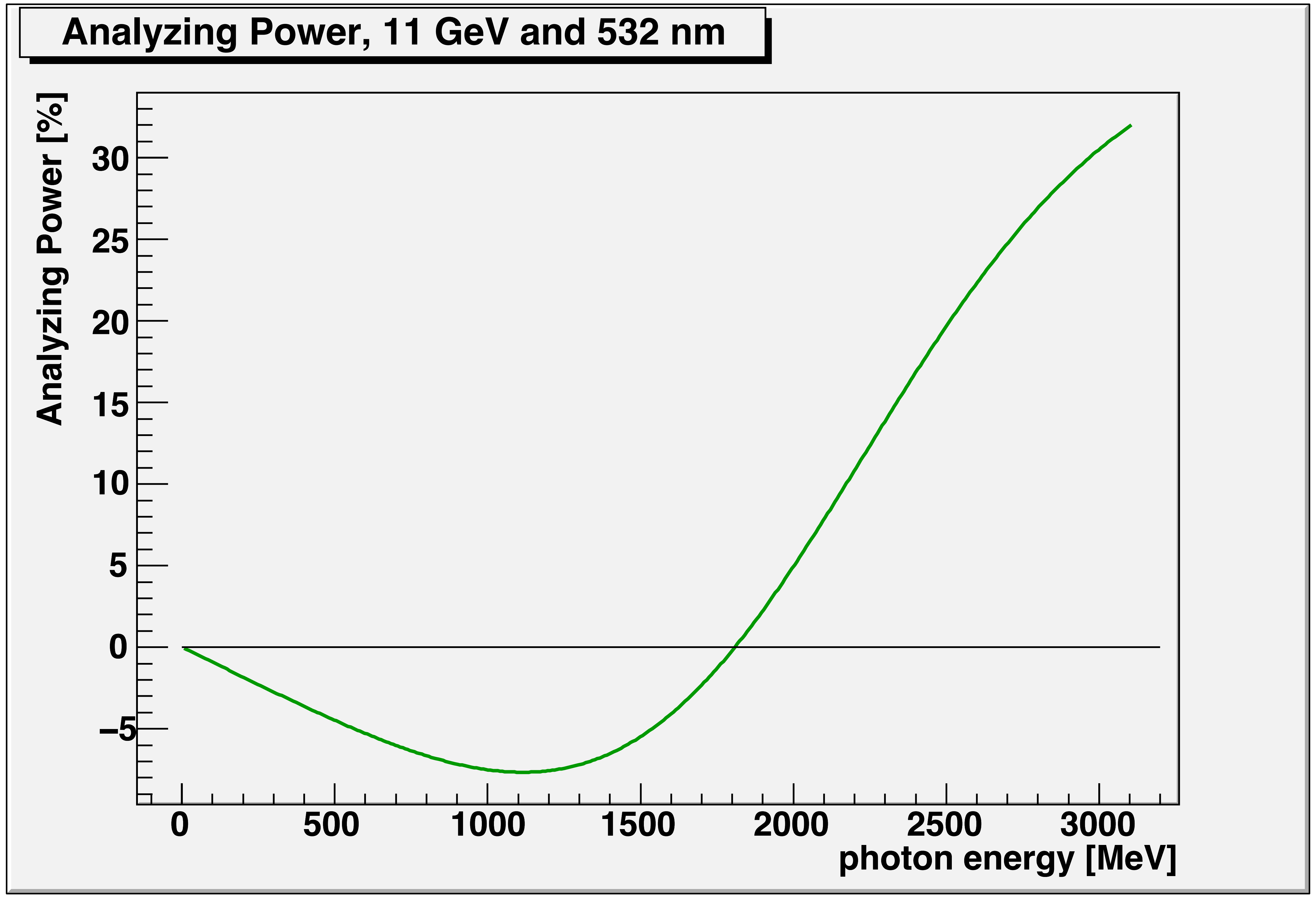
# Compton Spectrum



Compton edge

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

$$\rho = E_\gamma / E_\gamma^{max} \qquad E_\gamma \approx E_{\text{laser}} \frac{4a\gamma^2}{1 + a\theta_\gamma^2 \gamma^2} \qquad a = \frac{1}{1 + 4\gamma E_{\text{laser}}/m_e}$$

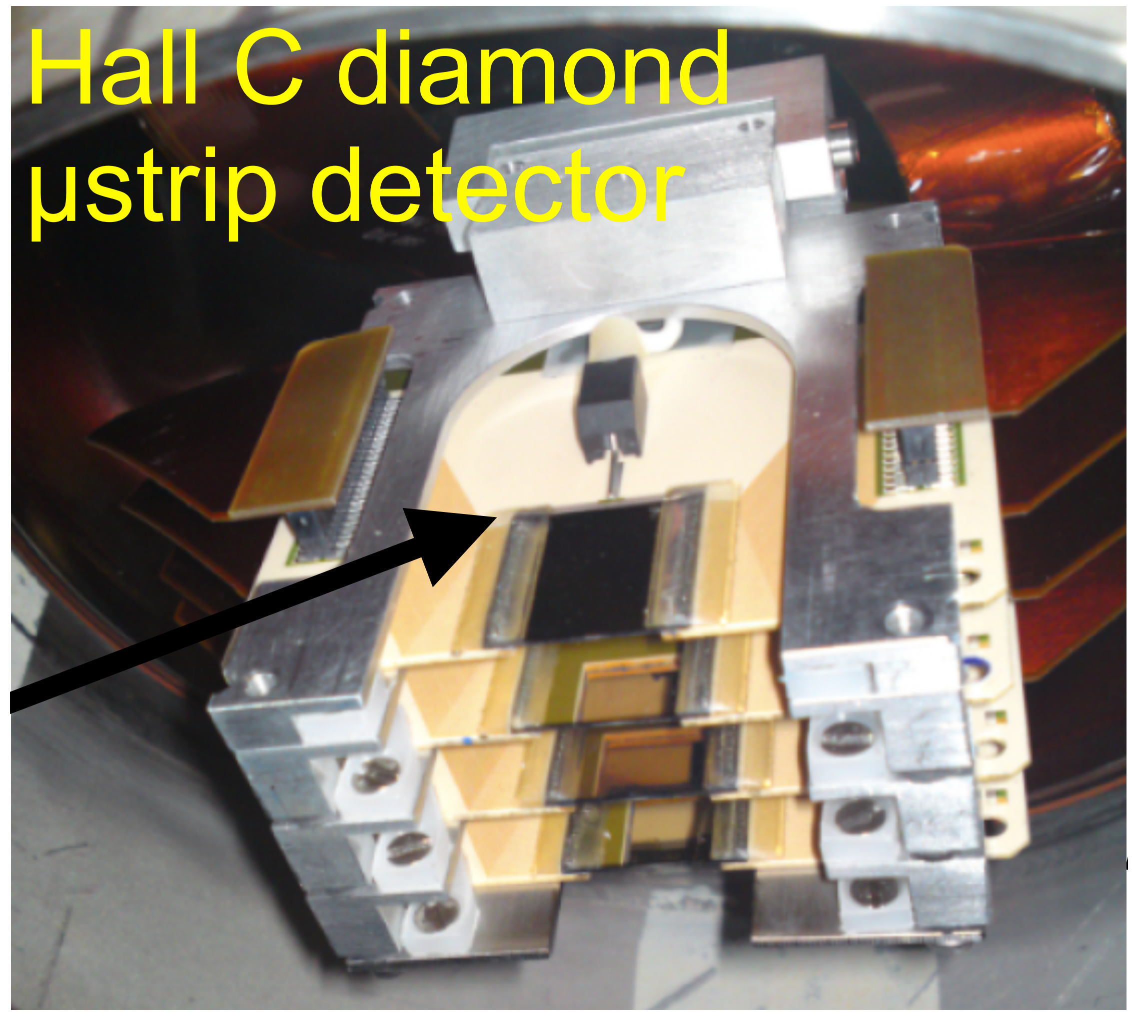


$$A_{\text{long}} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} (1 - \rho(1+a)) \left[ 1 - \frac{1}{(1-\rho(1-a))^2} \right]$$

# Landmarks in high precision Compton polarimetry

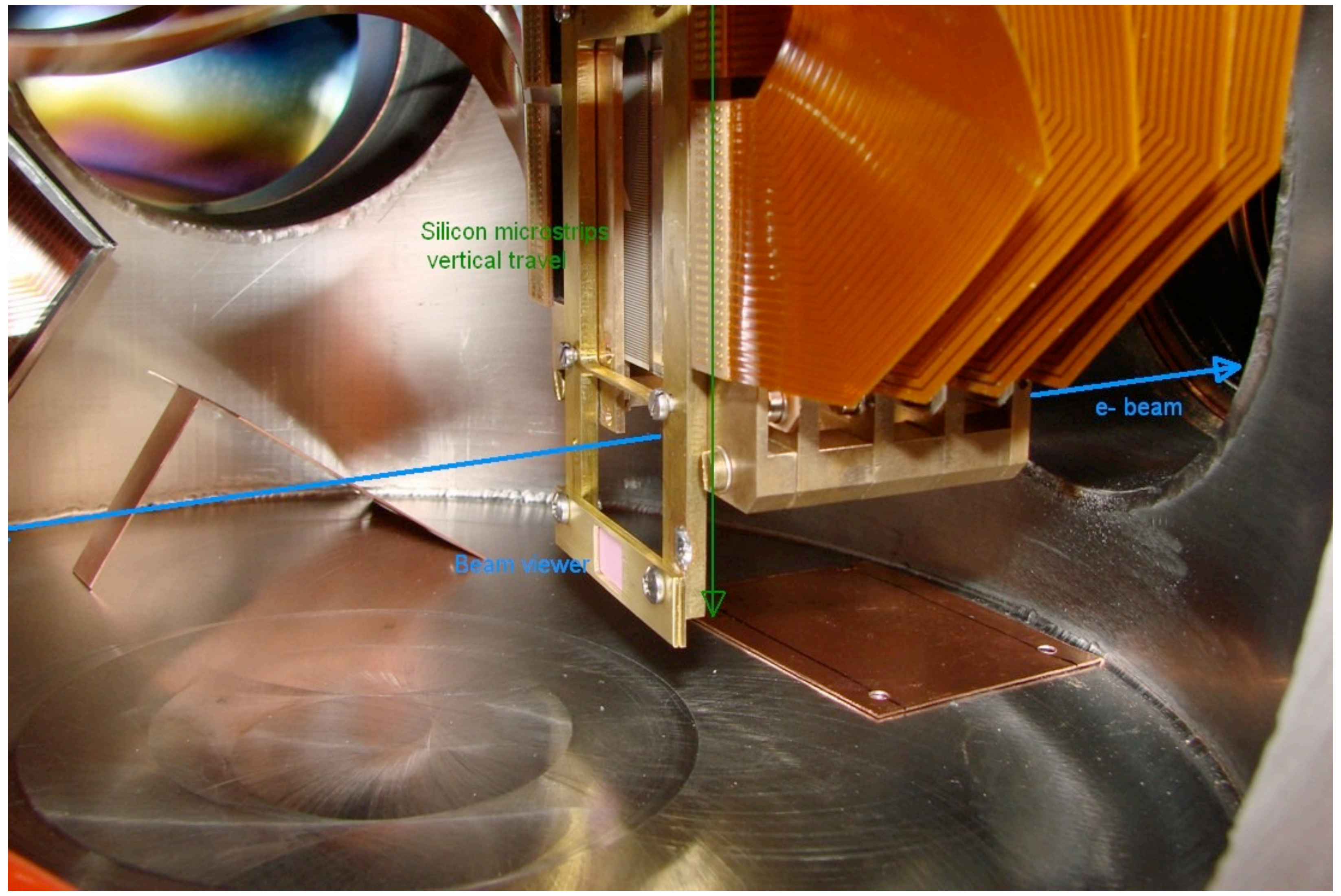
- Conceptual Design Report of a Compton Polarimeter for CEBAF Hall A - 1996
- Construction and first operations in Hall A: NIM A 443 (2000), NIM A 459 (2001), NIM A 551 (2005)
- Spin Dance 2000 Cross comparison of all JLab polarimeters Phys.Rev.ST Accel.Beams 7 (2004) 042802
- HAPPEX-II First high-precision electron detector result
- PREX-I, HAPPEX-3: First use of green (532nm) cavity, high precision integrating photon detection
  NIM A 676 (2012),NIM A 728 (2013), NIM A 822 (2016)
- Qweak (Hall C) High precision (0.6%) with a diamond microstrip electron detector *Phys.Rev.X* 6 (2016) 1, 011013
- CREX 0.4% precision, with integrating photon detection Phys.Rev.C 109 (2024) 2, 024323

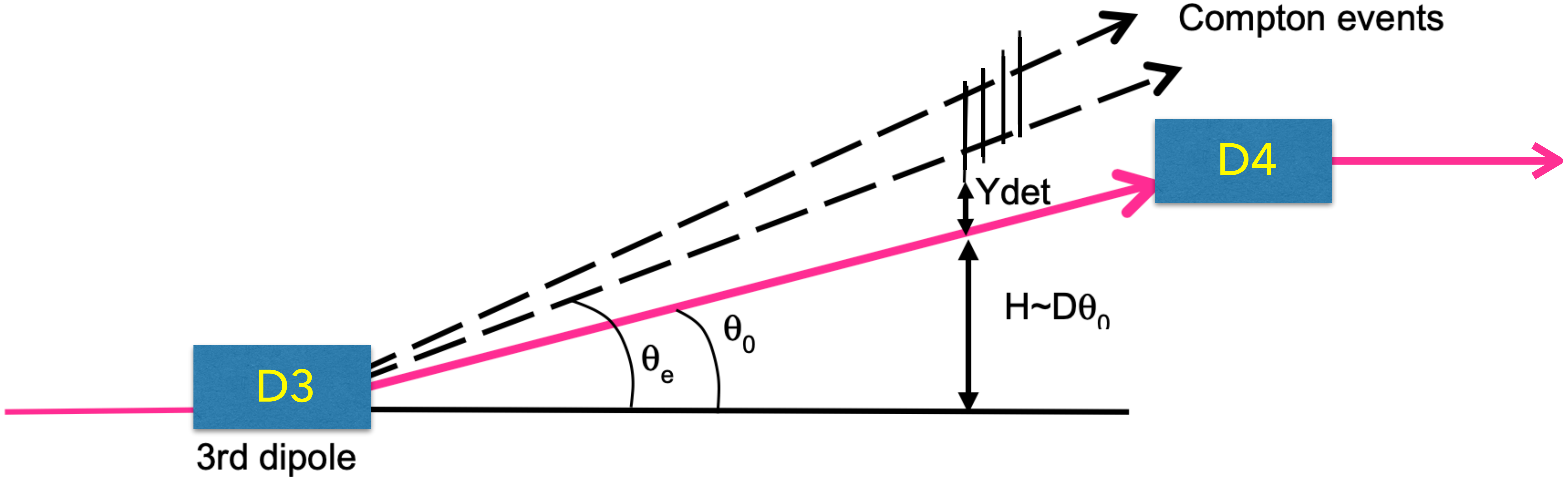
# Electron Detector



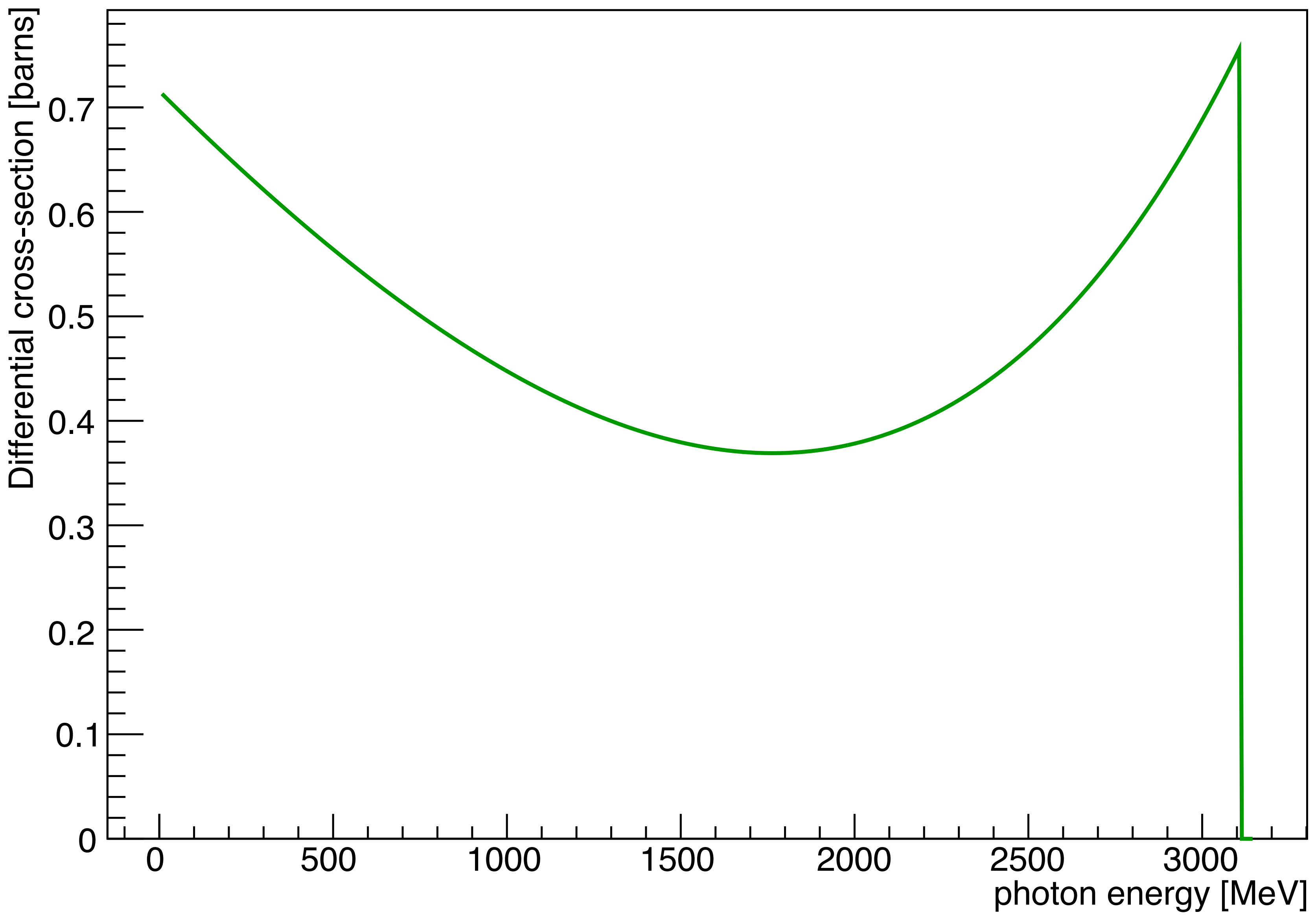
Previously: microstrip detectors

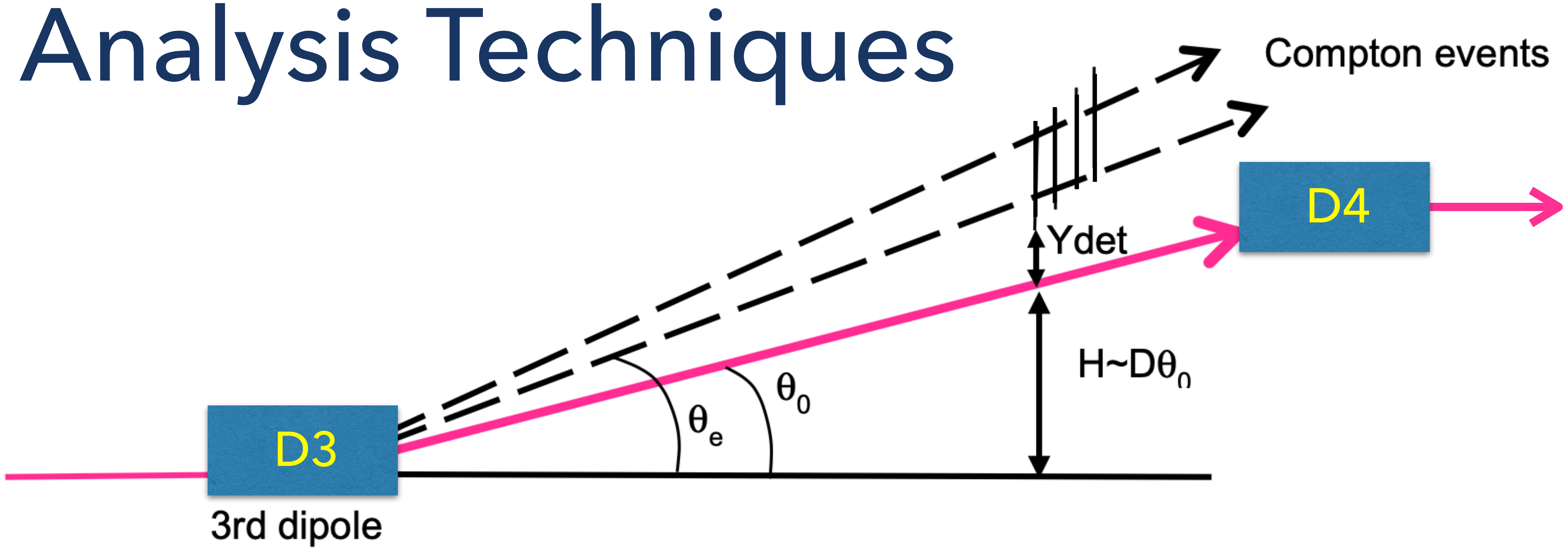
- only one readout direction (dispersive)
- measures position relative to primary beam ⟶ $\rho = E_\gamma / E_{\gamma,max}$
- Multiple planes, useful for reducing noise but otherwise perhaps not needed
- Simple road finding tracking (everything of interest has a well-defined angle)



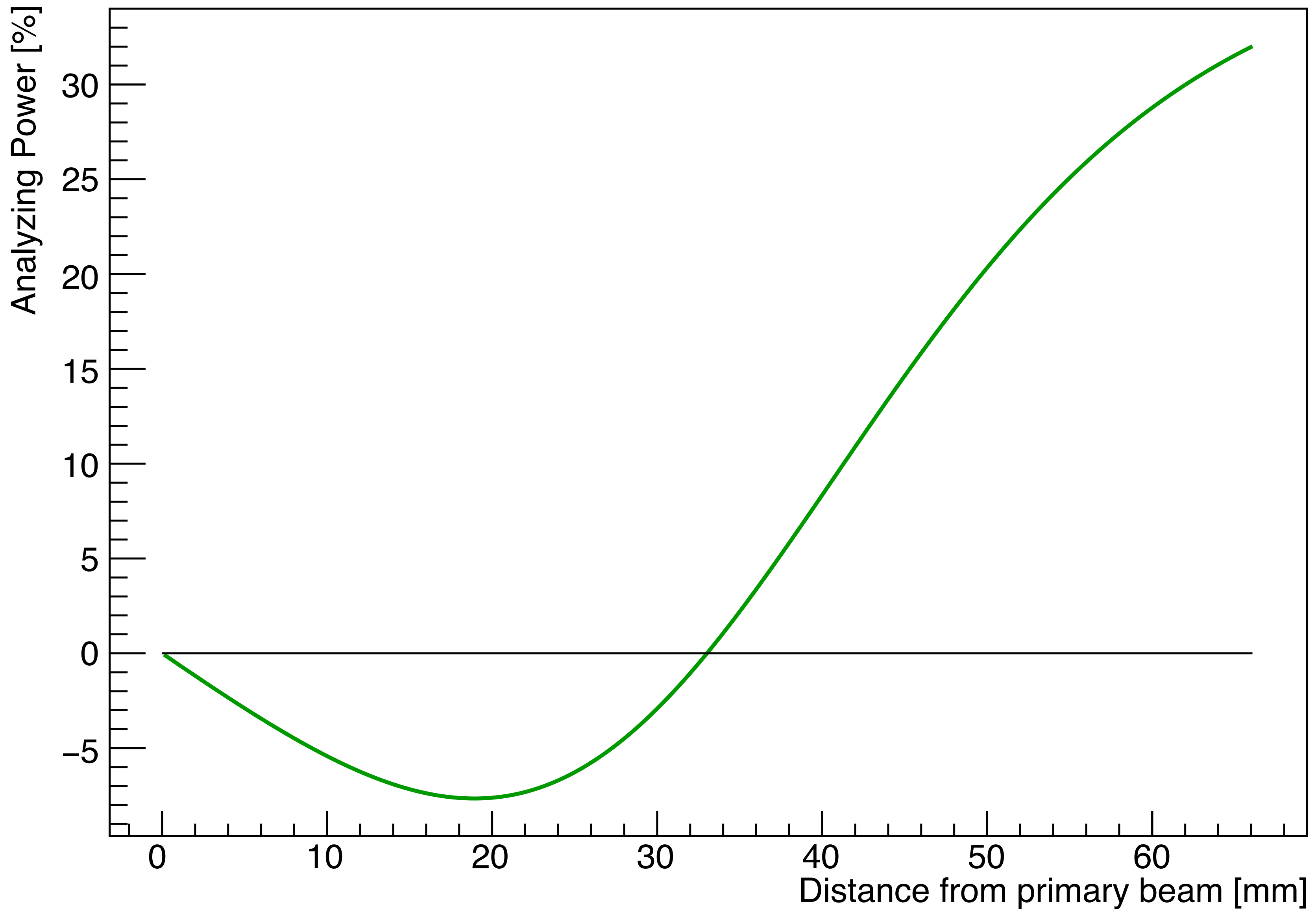


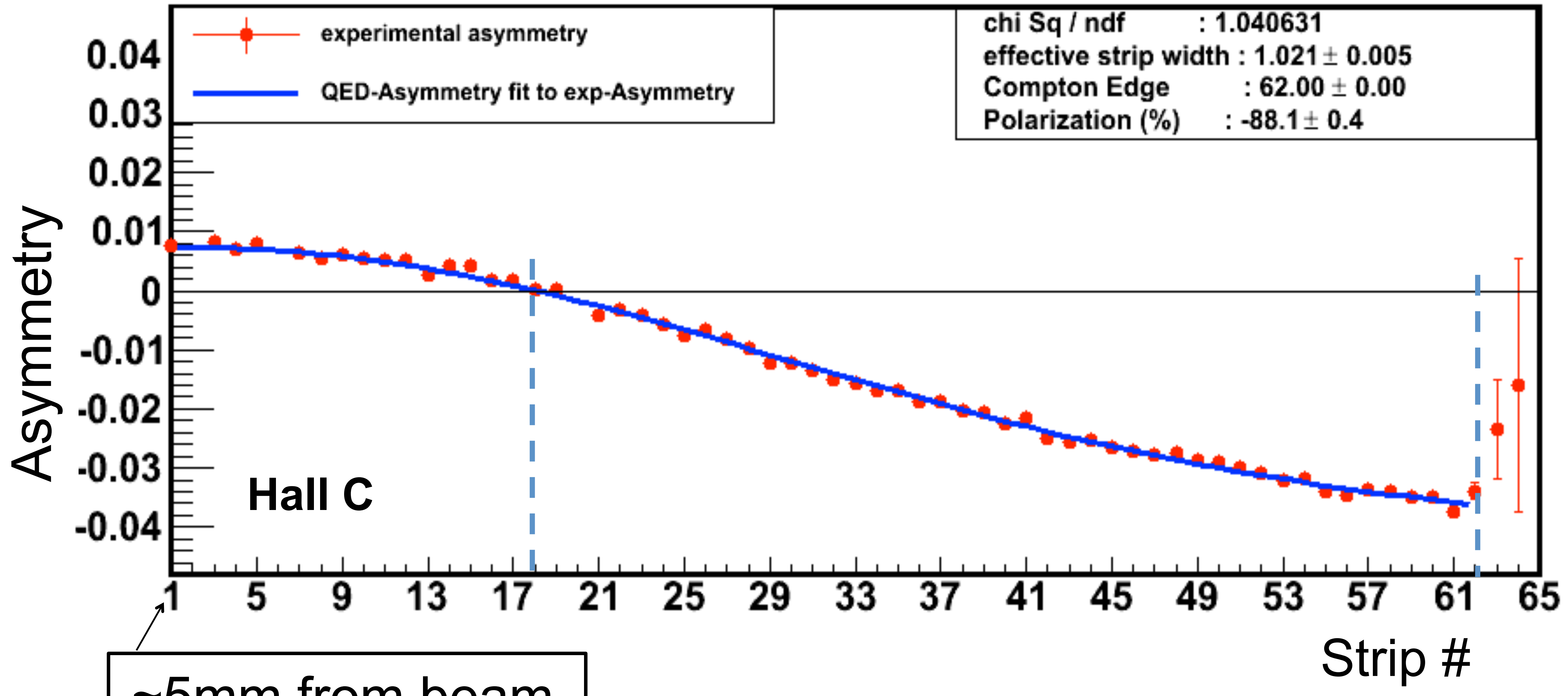
# Electron Analysis Techniques





Excellent response function is assumed: strip width / $Y_{max}$





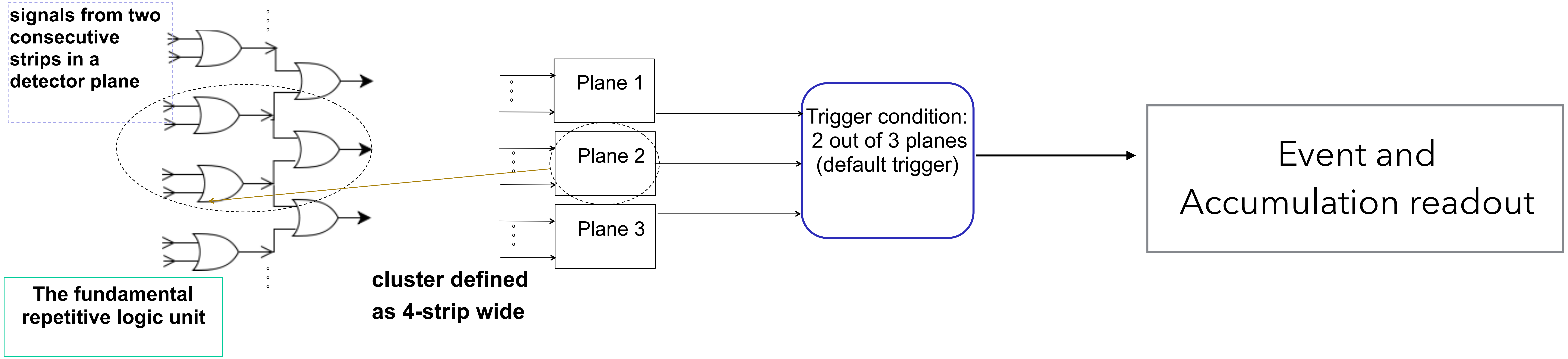
~5mm from beam

Phys.Rev. X6 (2016) no.1, 011013

# Previous triggering and DAQ - Qweak

## Track-finding Trigger

Marched along in FPGA



signals from two consecutive strips in a detector plane

The fundamental repetitive logic unit

cluster defined as 4-strip wide

Plane 1

Plane 2

Plane 3

Trigger condition:
2 out of 3 planes
(default trigger)

Event and Accumulation readout

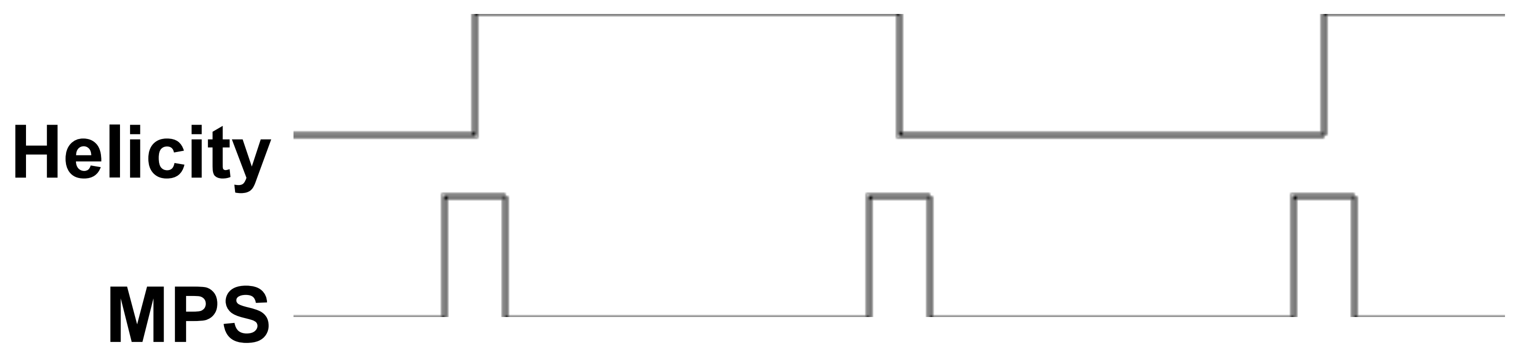
D. Dutta

**Data collected simultaneously in three modes:**

**Event mode** : **snapshot of all detector strips is recorded for every trigger** **(prescaled)**

**Scaler mode** : **every hit on each detector strip is counted without requiring trigger** **(un-gated by mistake)**

**Accumulation mode** : **hits that satisfy the trigger condition are counted and histogrammed internally** **(gated by MPS)**



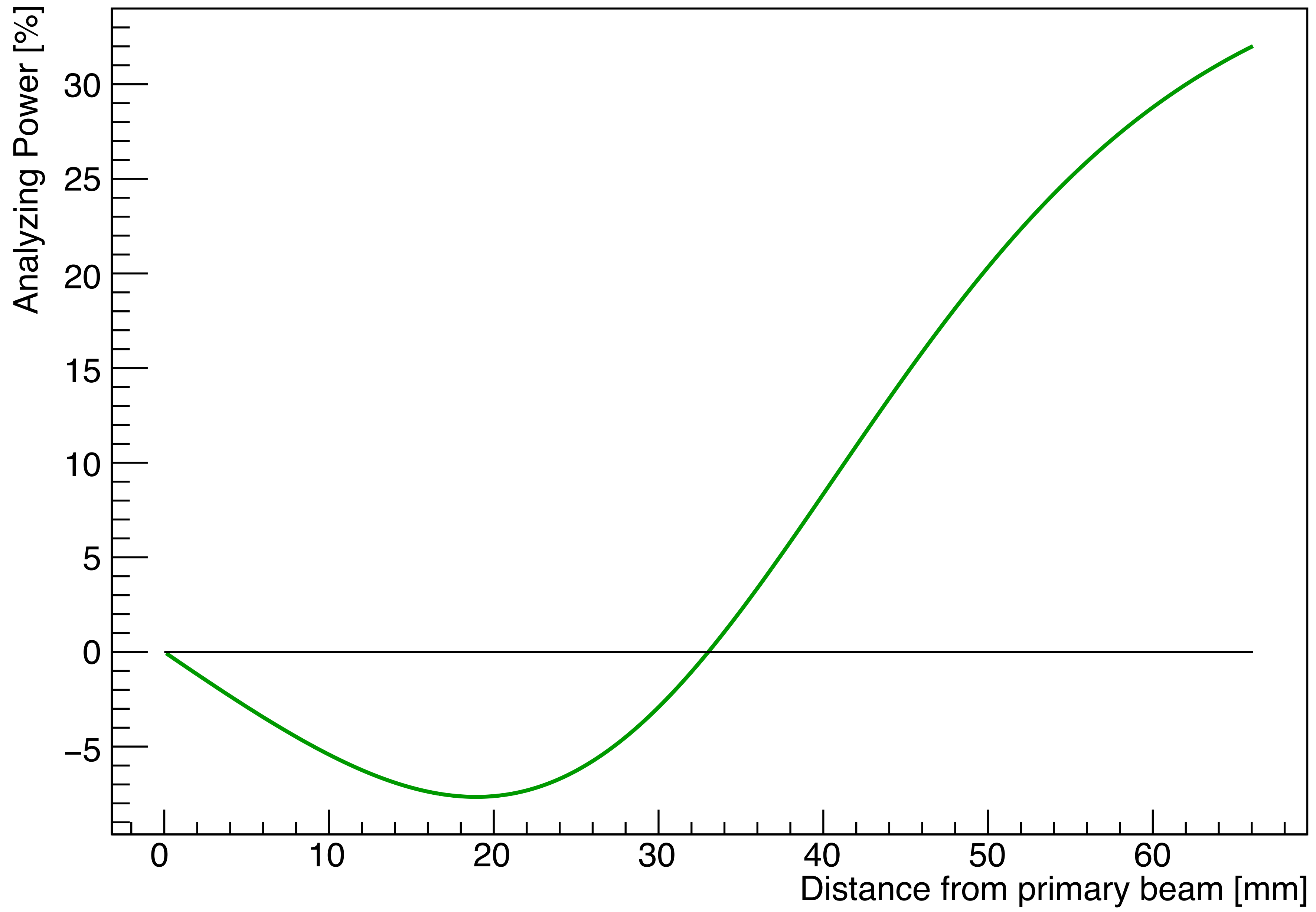
# Calibrating the electron spectrum

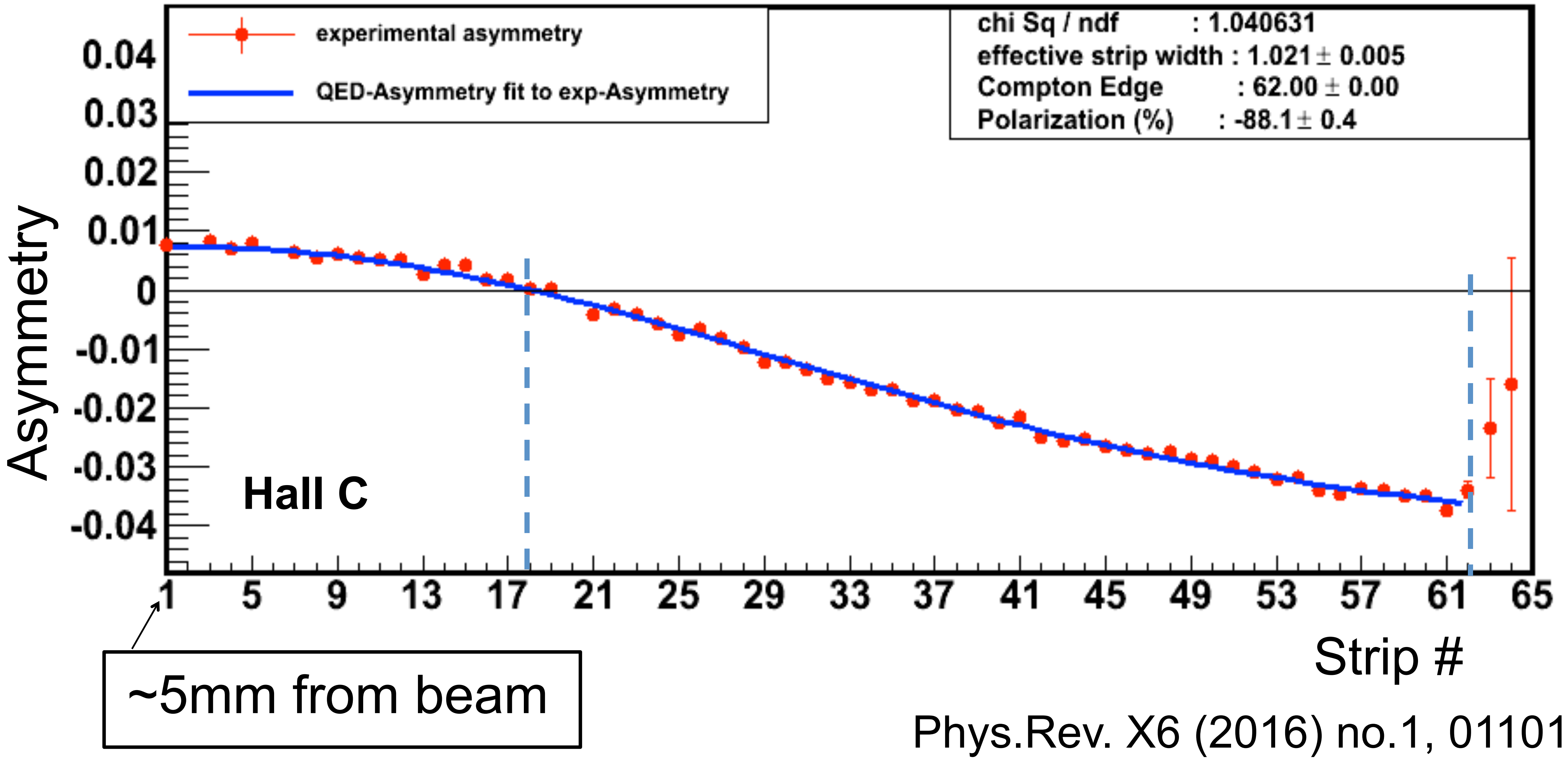
Hit spectrum over strip number $\longrightarrow$ $p_e$ $\longrightarrow$ $\rho = E_\gamma / E_\gamma^{max}$

To calibrate, you can use:
- Compton edge + “known” dispersion
- Compton edge + zero crossing
- Fit to full shape of asymmetry

To extract polarization, you can use:
- All measured strips
- One or few strips near the Compton edge
- One or few strips at the $A_p$ minimum

*Qweak used a fit, and all measured strips*



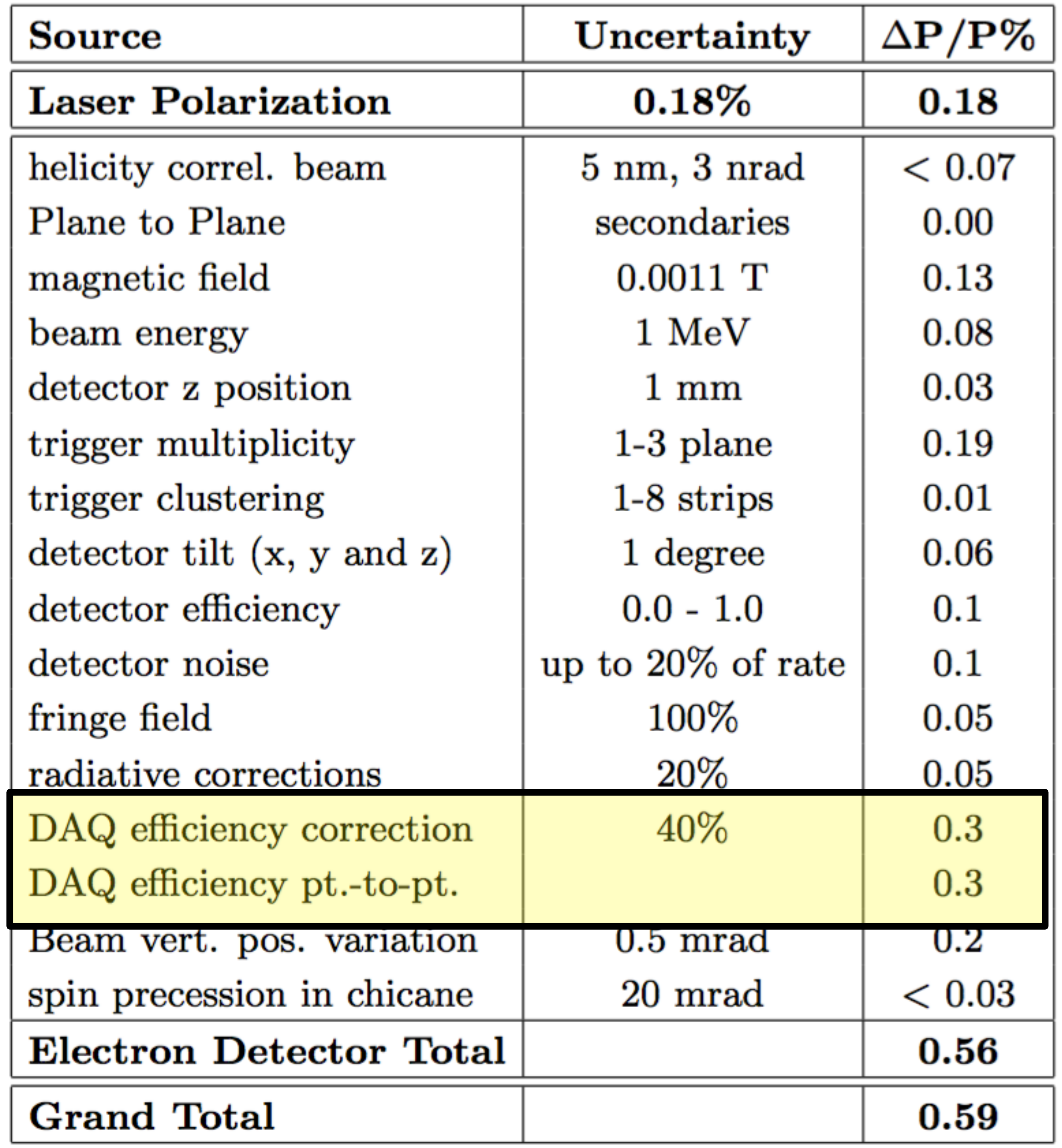


~5mm from beam

Phys.Rev. X6 (2016) no.1, 011013

# Qweak (Hall C) Compton result

Qweak used only the electron detector for the polarimetry result



| Source | Uncertainty | ΔP/P% |
|---|---|---|
| **Laser Polarization** | **0.18%** | **0.18** |
| helicity correl. beam | 5 nm, 3 nrad | < 0.07 |
| Plane to Plane | secondaries | 0.00 |
| magnetic 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, y and z) | 1 degree | 0.06 |
| detector efficiency | 0.0 - 1.0 | 0.1 |
| detector noise | up to 20% of rate | 0.1 |
| fringe field | 100% | 0.05 |
| radiative corrections | 20% | 0.05 |
| DAQ efficiency correction | 40% | 0.3 |
| DAQ efficiency pt.-to-pt. |  | 0.3 |
| Beam vert. pos. variation | 0.5 mrad | 0.2 |
| spin precession in chicane | 20 mrad | < 0.03 |
| **Electron Detector Total** |  | **0.56** |
| **Grand Total** |  | **0.59** |

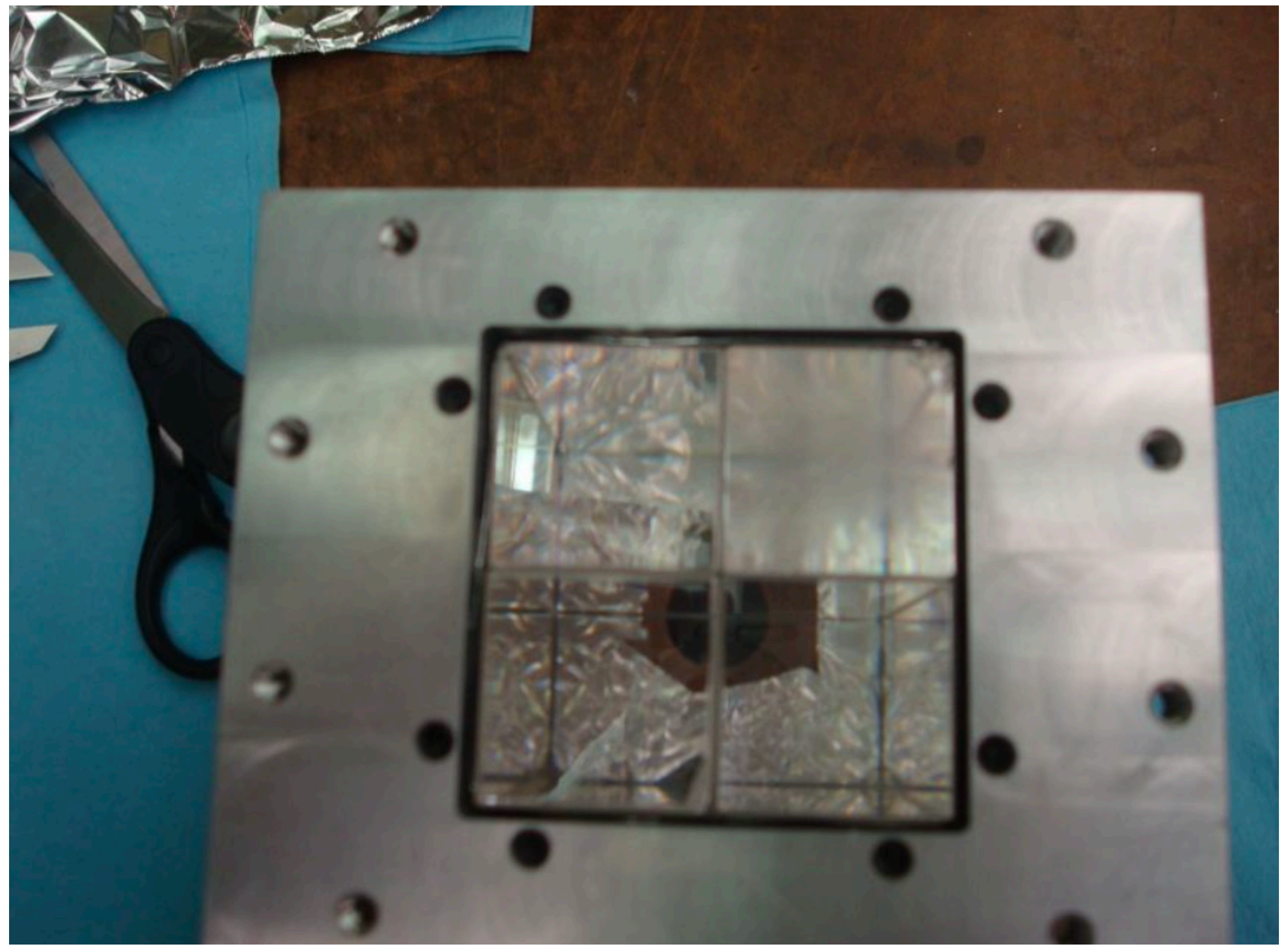
NOTE: dominant uncertainty from known and understood DAQ design flaws.

MODELSIM used to simulation FPGA coding, clarified efficiency / deadtime issues

This kind of modeling of even a simple trigger is critical: high precision measurements of a counting asymmetry require a thorough understanding of the effects of noise, efficiency and signal overlap when processed through the DAQ

# Photon Detector

We require a large, dense photon detector that can contain the shower up to ~3 GeV $\gamma$



2x2 stack of $PBWO_4$
- 6x6 cm x 20 cm length (total)
- On loan from Yerevan/Hall C
- Stryrofoam wrapped for thermal stability
- Much lower light production compared to smaller scintillating crystal used for low-energy (GSO)
- Crucially: this scintillator has no detected long-lived fluorescence
- Tungsten "Jaws" remote variable collimator in front of detector cut synchotron radiation from D2 and D3 bends.

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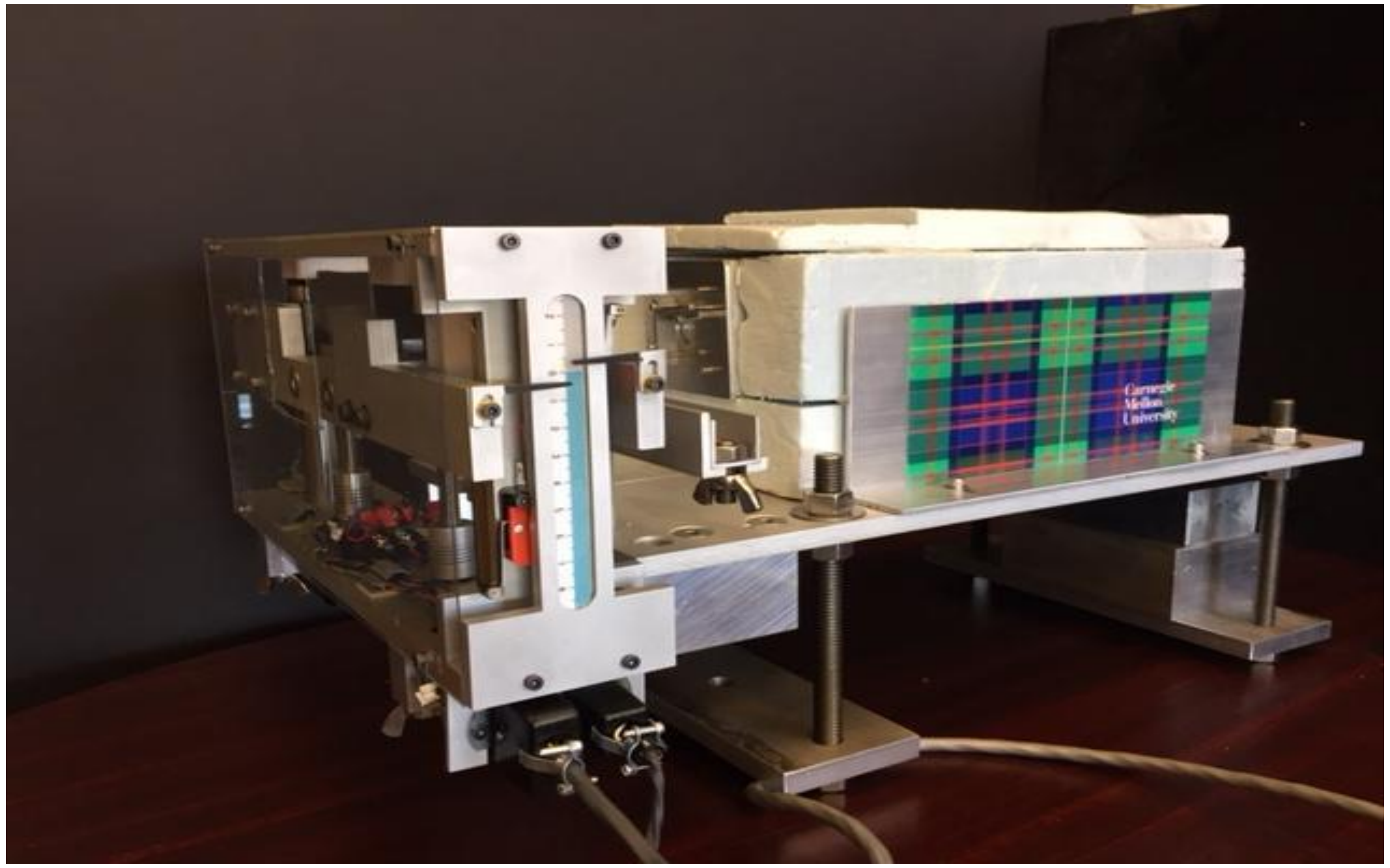

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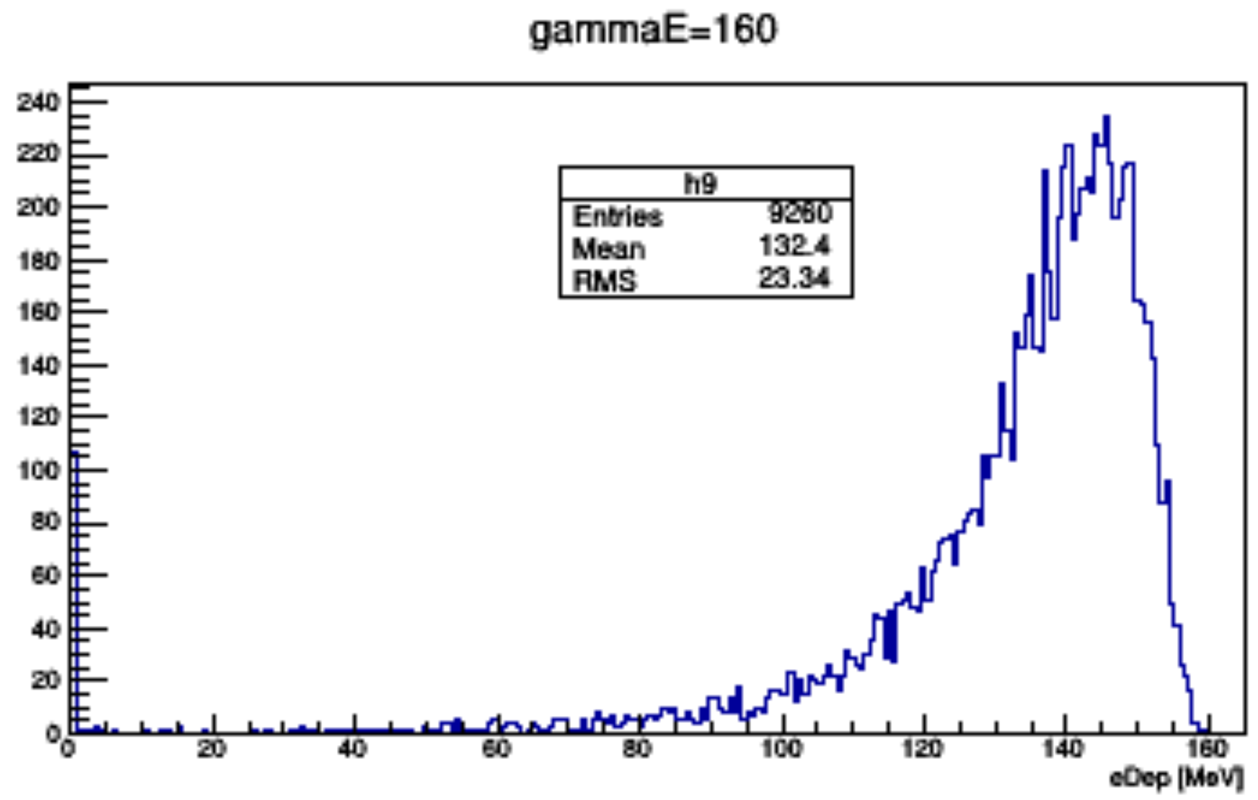
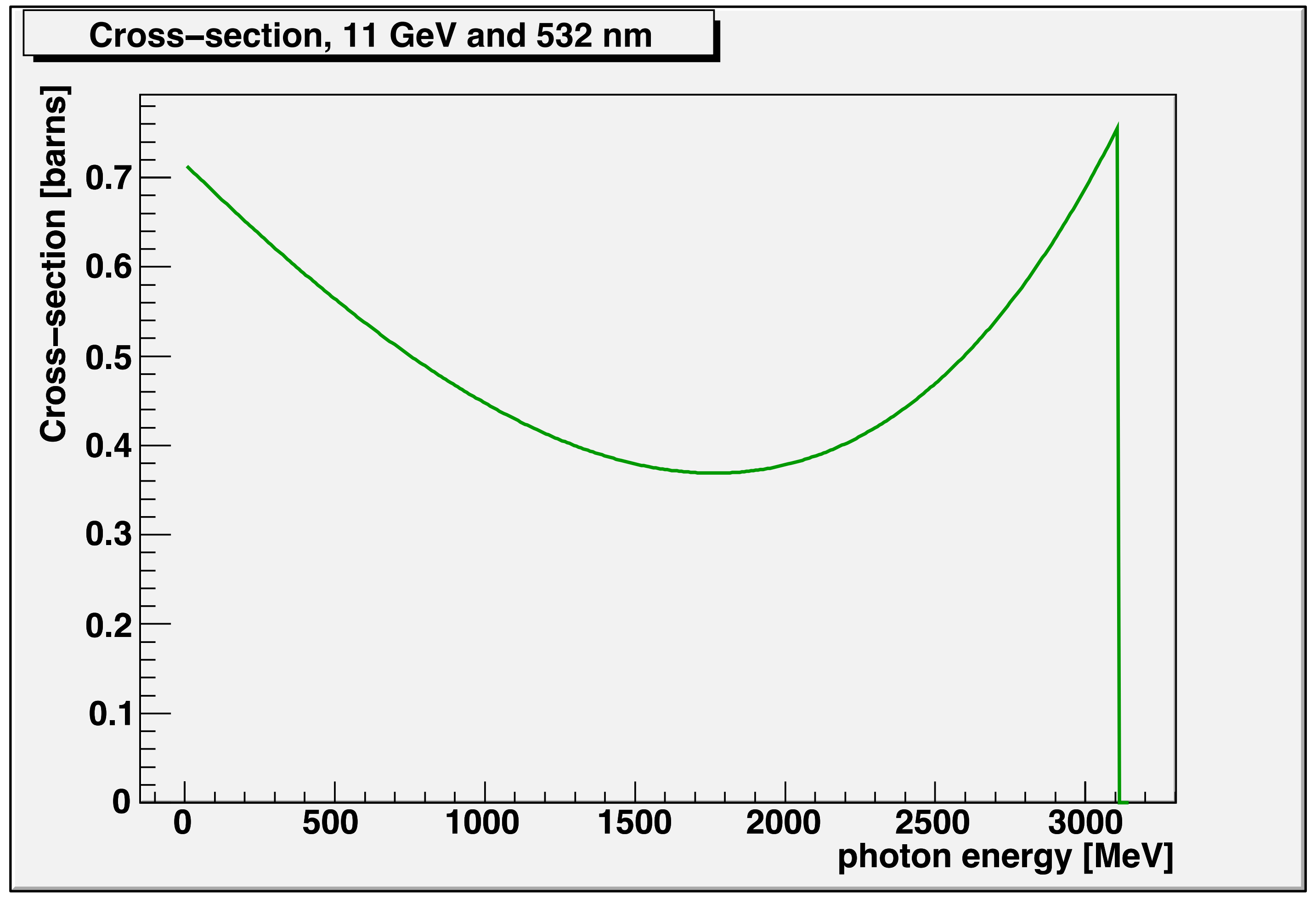
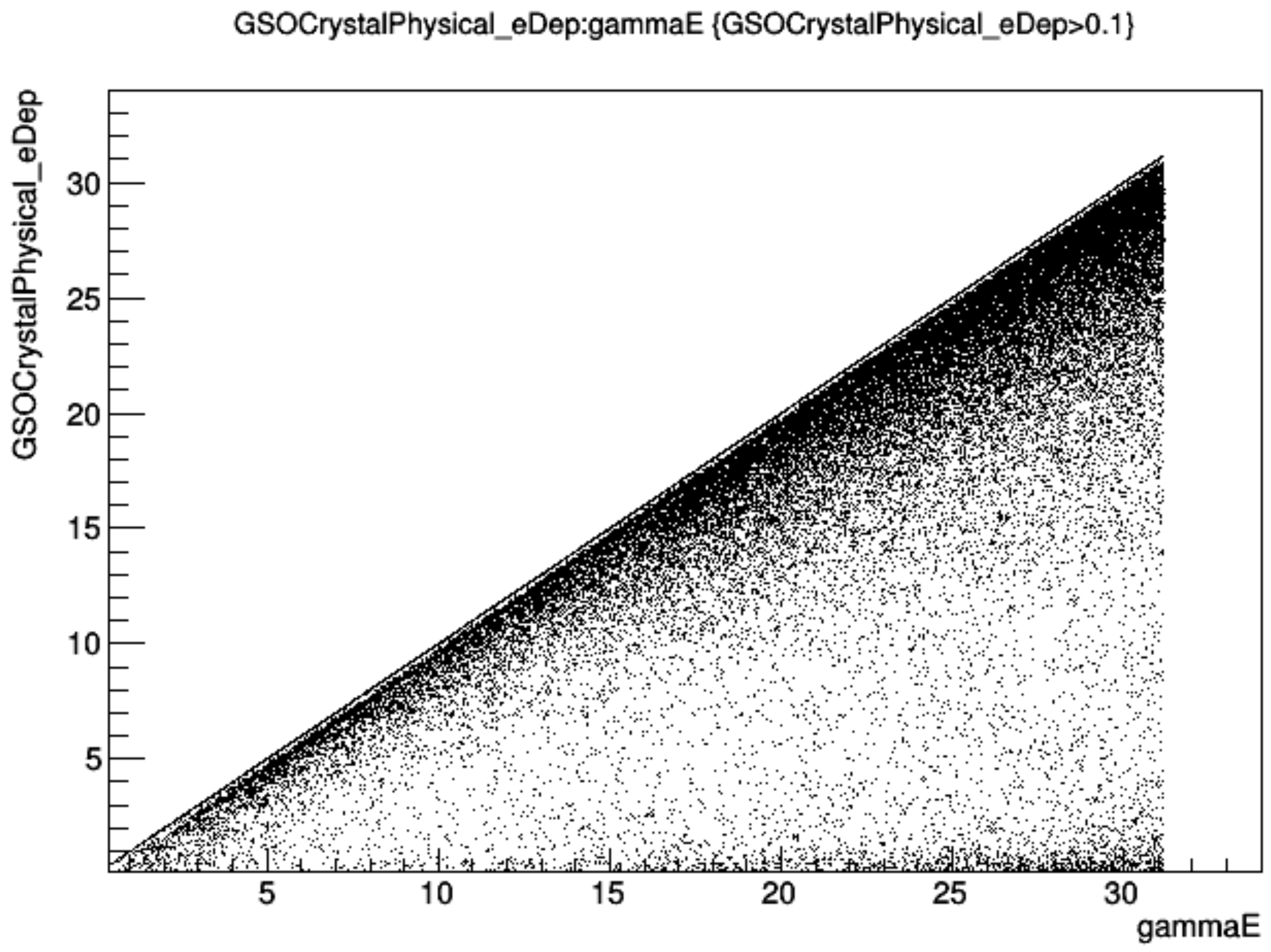
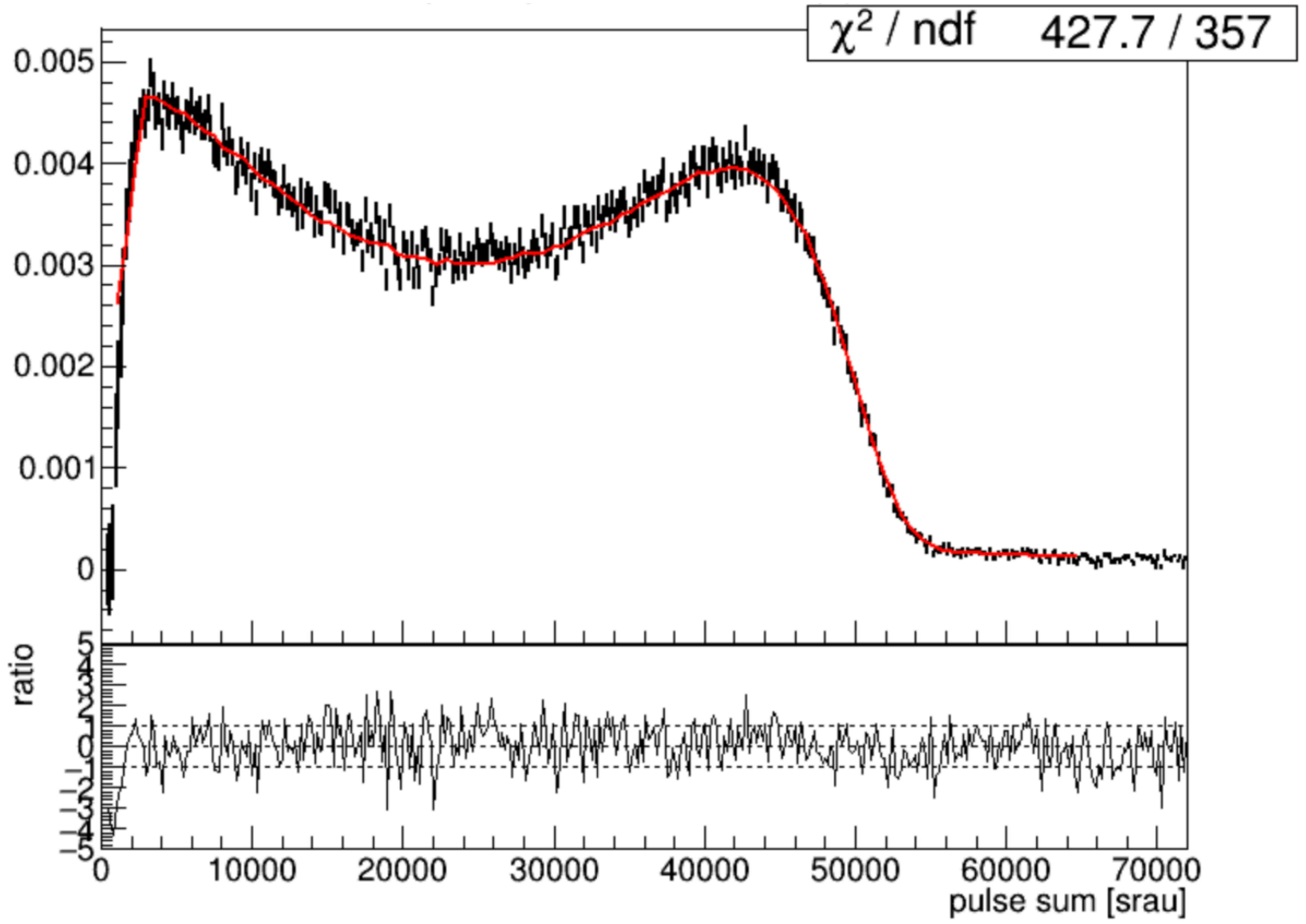
# Photon Detector Response functions

simulations of GSO response









# Photon analysis techniques

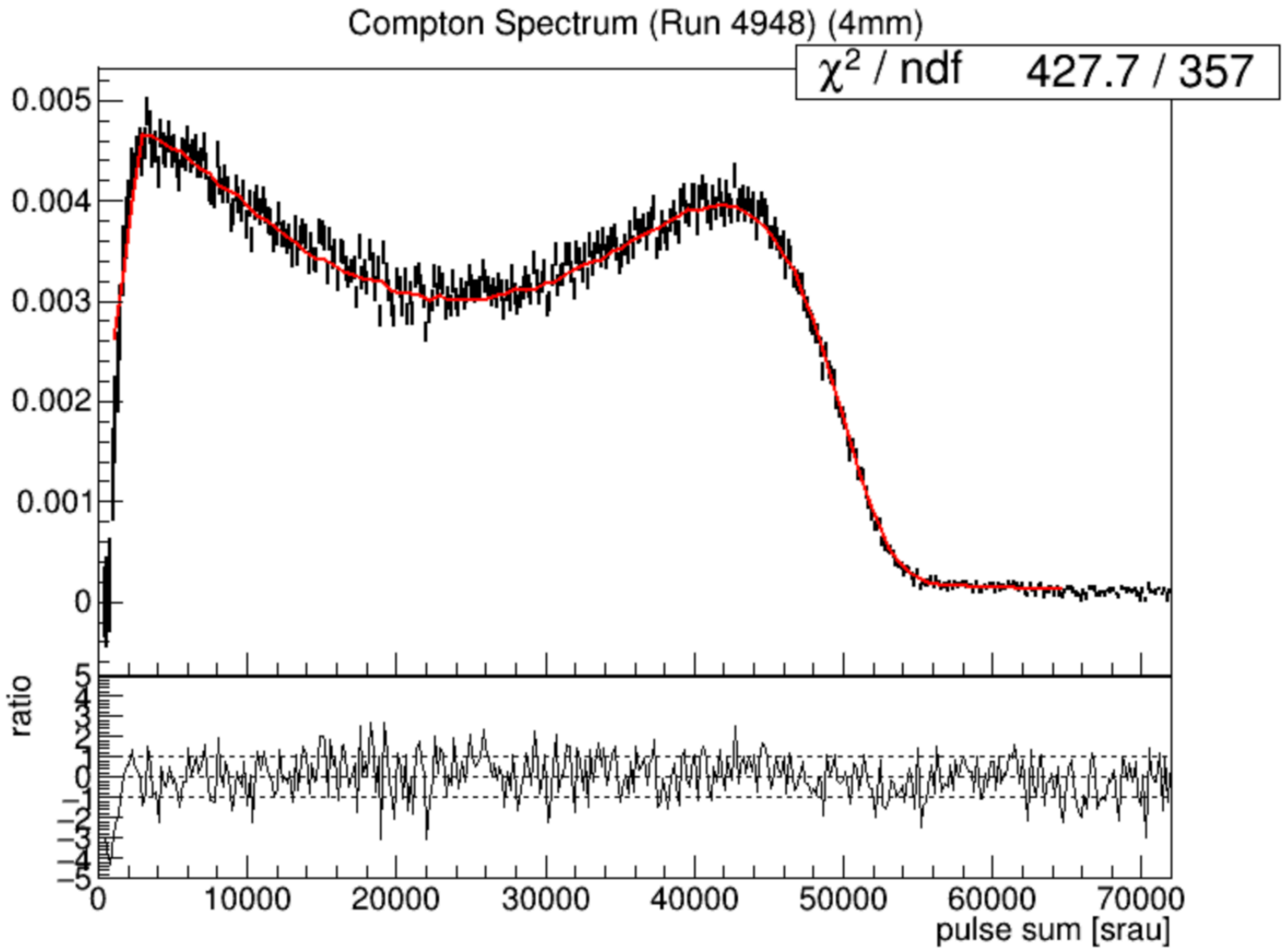
**Photon counting** collect each pulse and histogram pulse integral Y. As asymmetry as a function of pulse integral A(Y) convolutes A(E) and Y(E).
Sensitive to most of all to response function calibration - the cut-off at trigger threshold is a mine field!

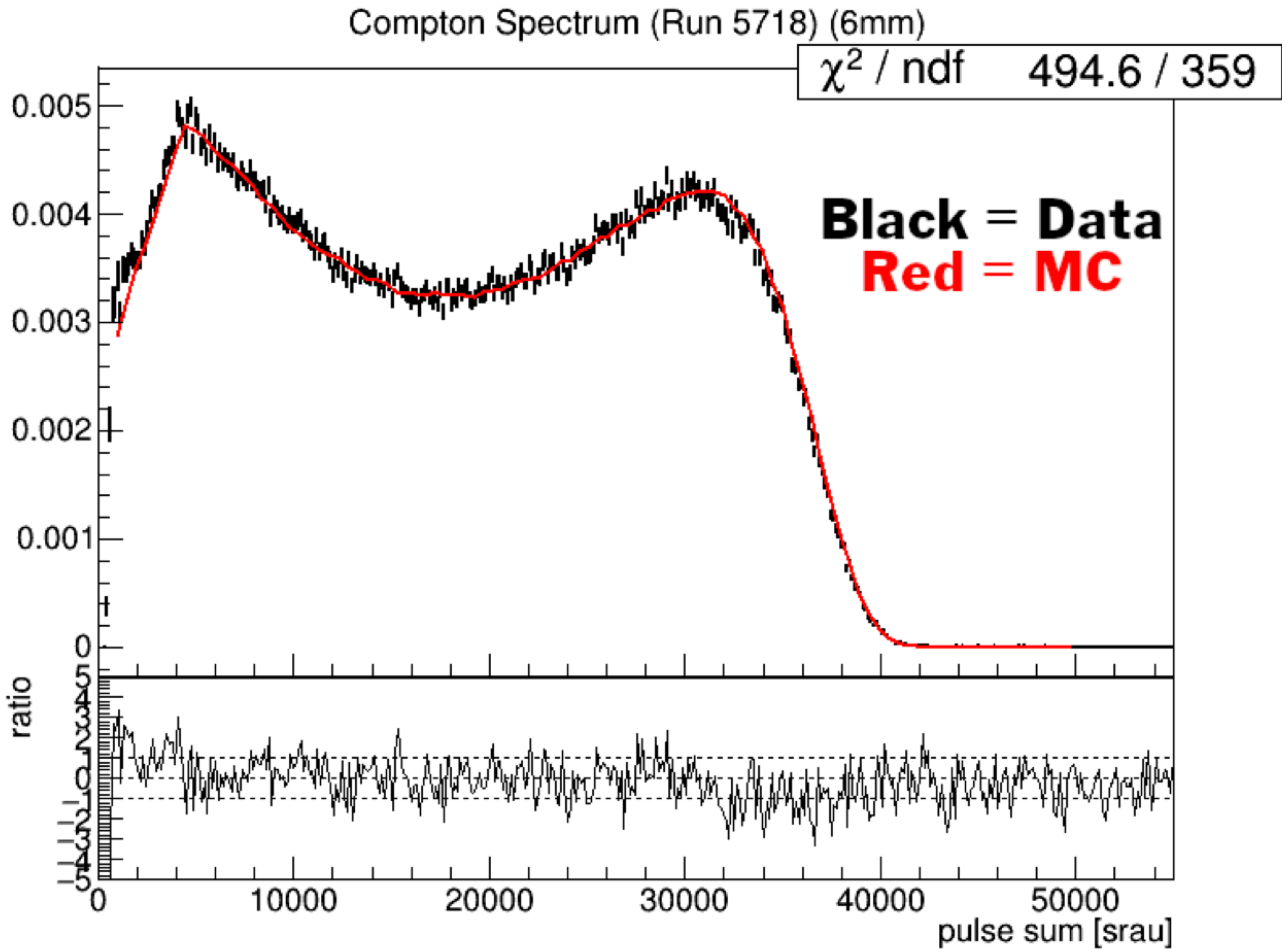
**Photon integration** Like the main experiment: integrate total PMT current during helicity windows, and form an asymmetry. However, signal is significant over background, so requires background subtraction. Sensitive to linearity, varying backgrounds, and photon acceptance.

Measuring the spectrum is still crucial, to verify acceptance/response model.

# Photon acceptance

photon acceptance cut by misalignment to collimator



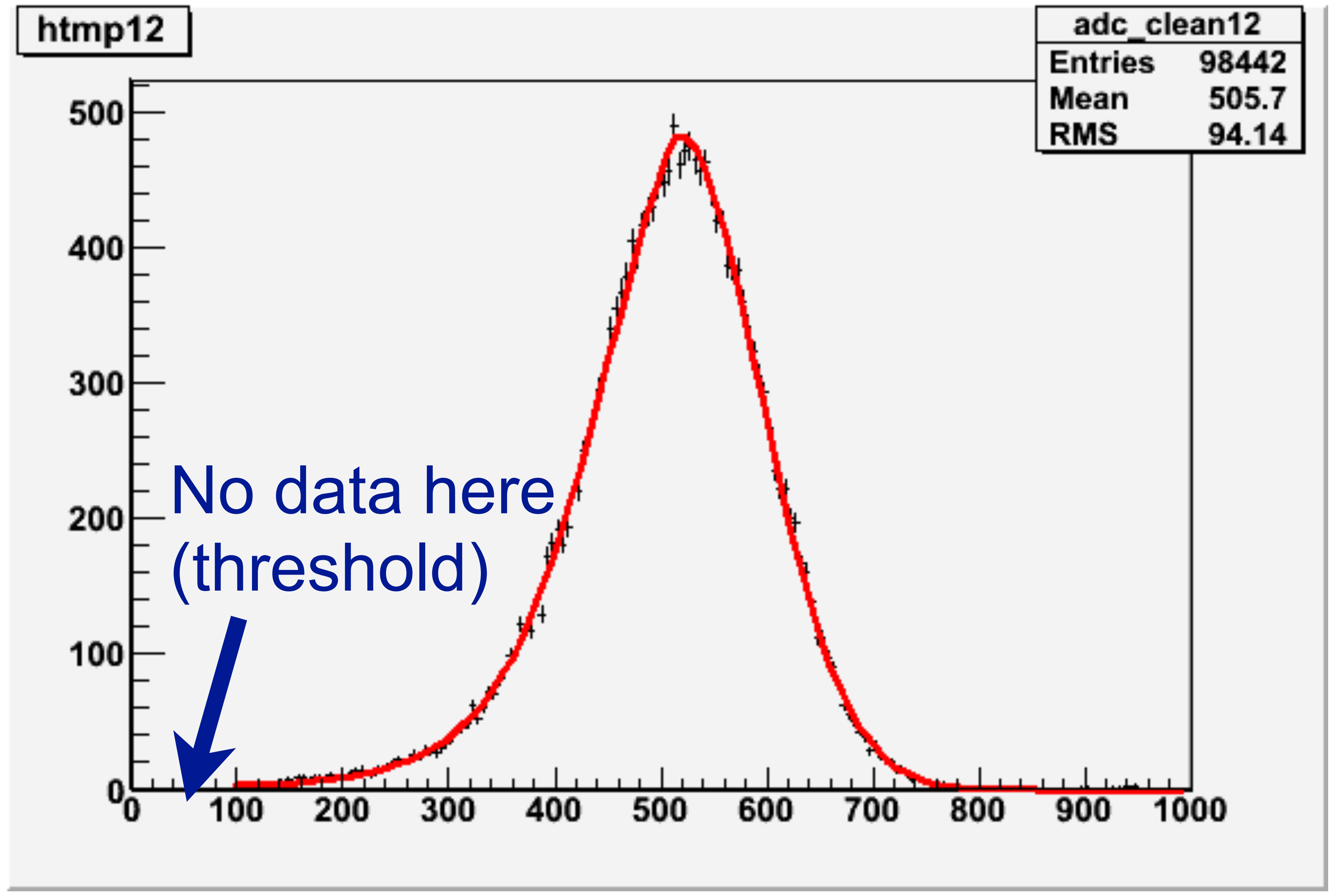


**Black = Data**
**Red = MC**

# e-$\gamma$ coincidence: response function calibration

- Electron-photon coincidence
- low-rate trigger (prescaled)
- Photon discriminator threshold and minimum $e^-$ detector approach leaves some portion of the response function unmeasured....

**Photon detector response in coincidence with single e-det strip**



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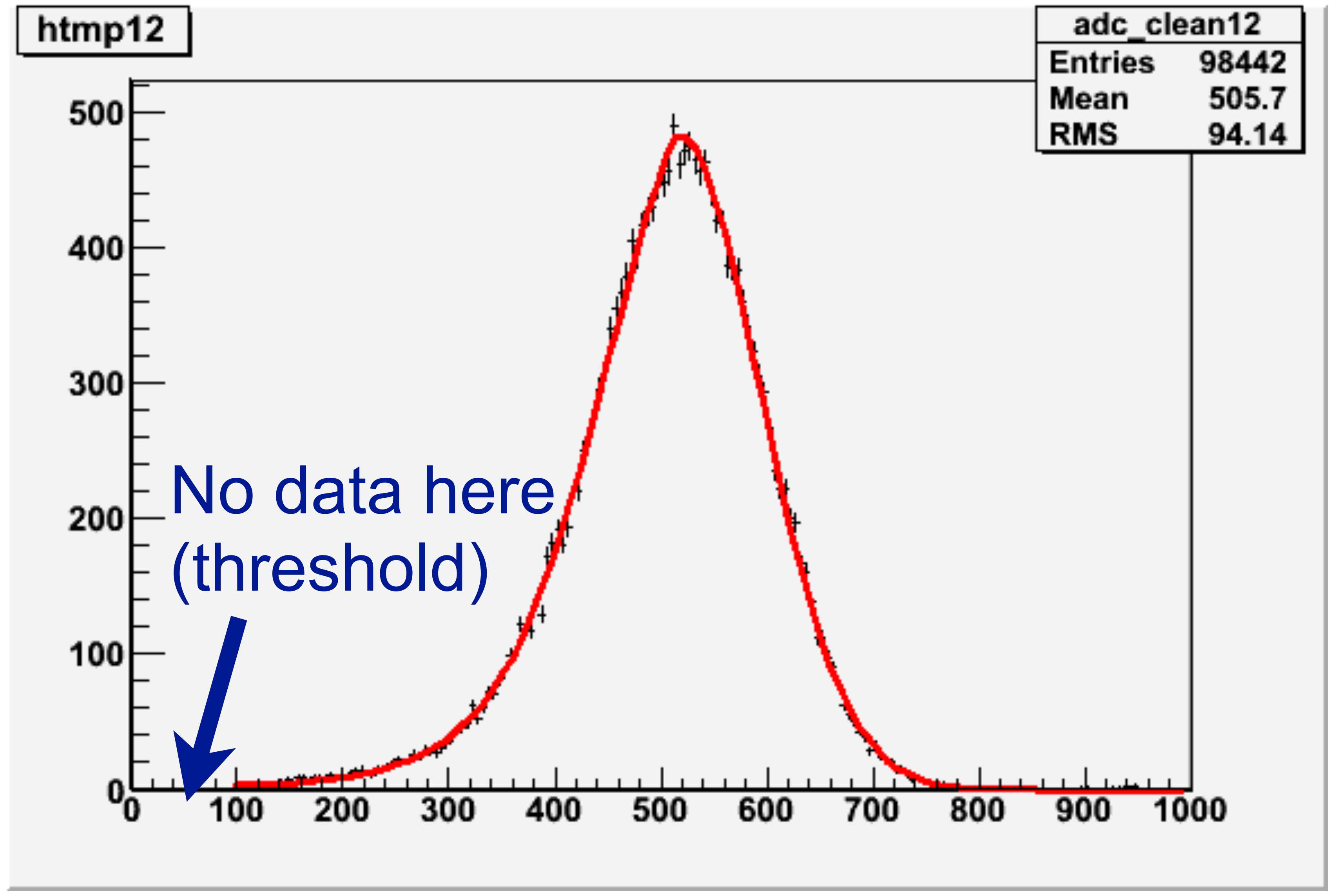
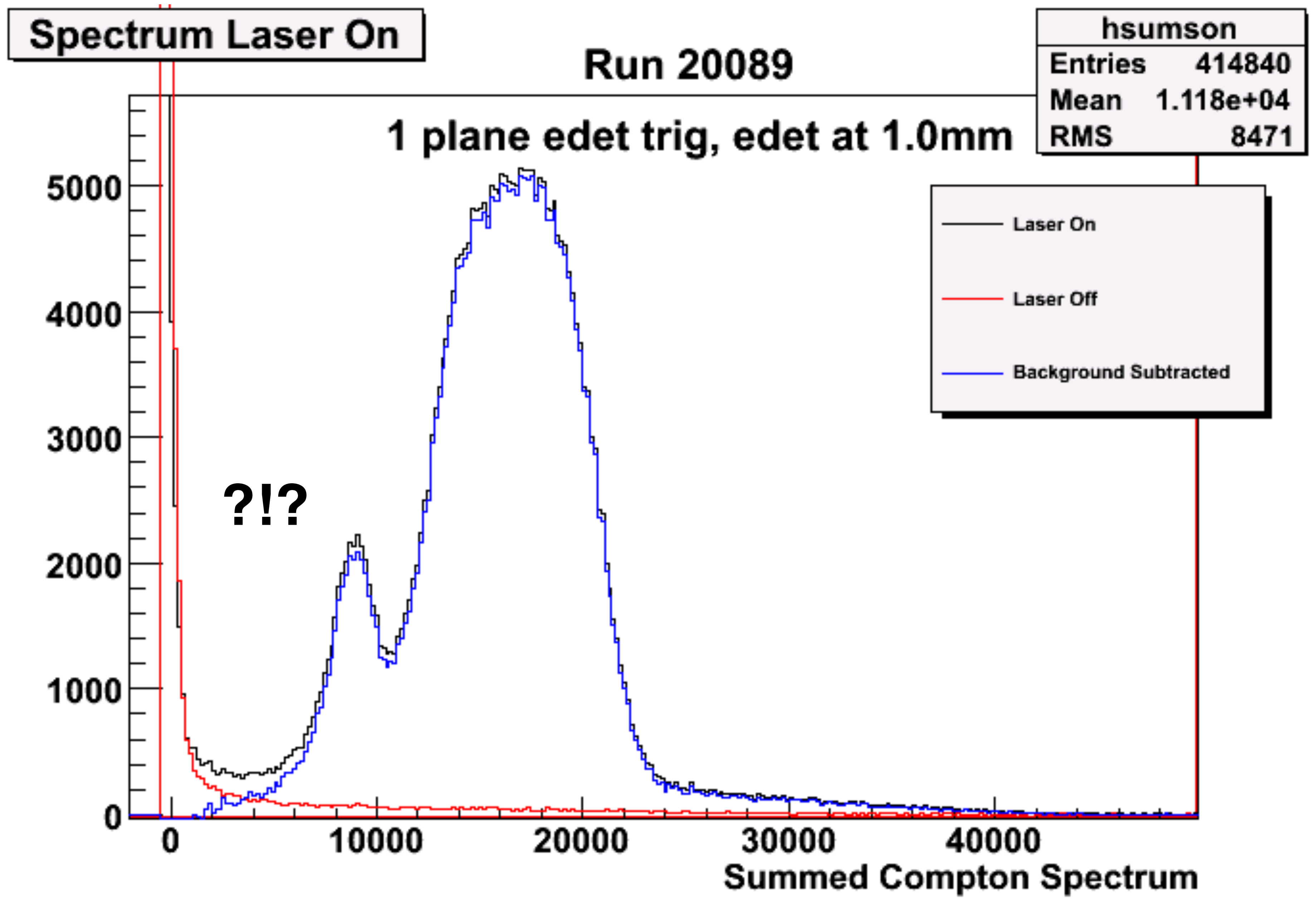


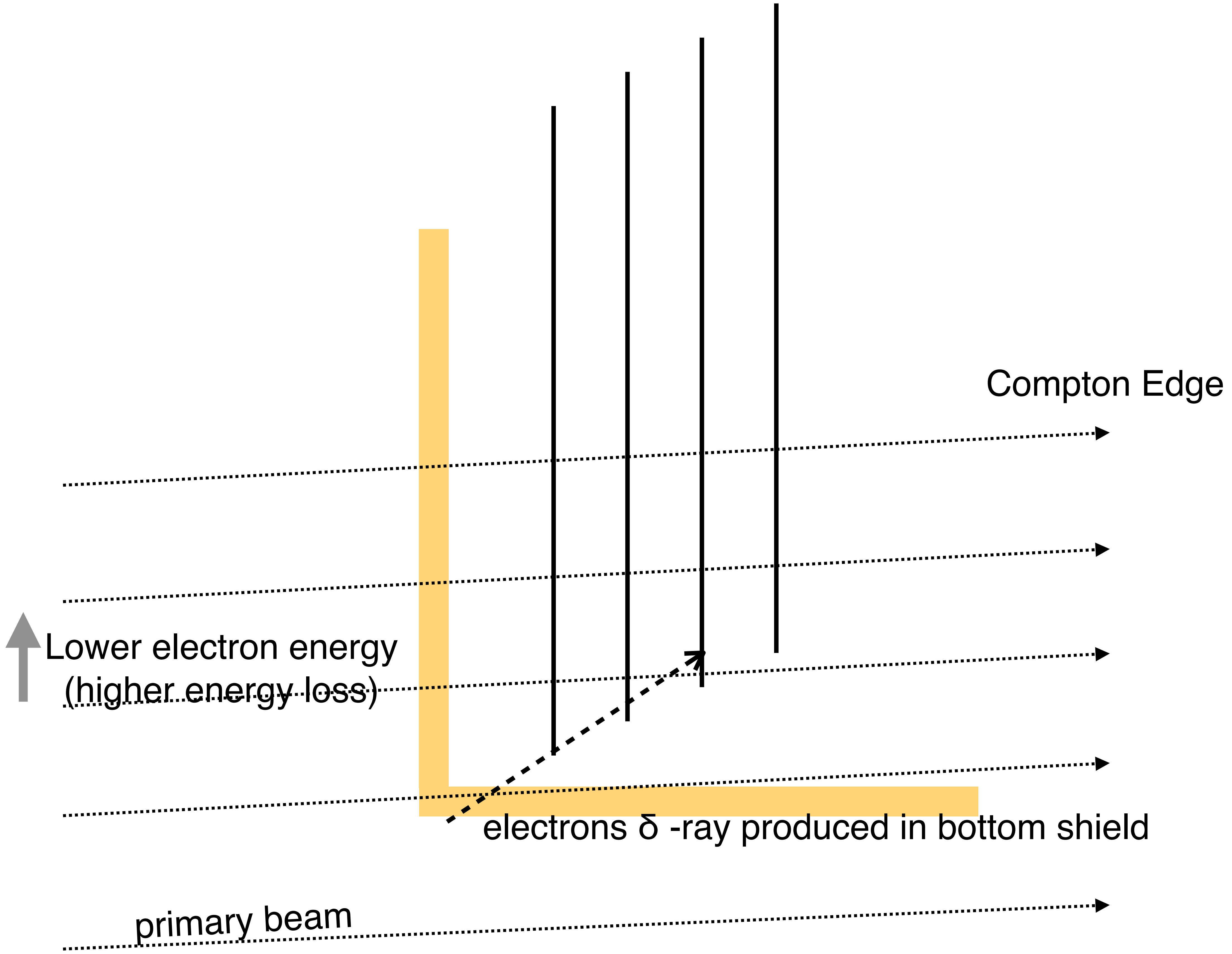
No data here (threshold)

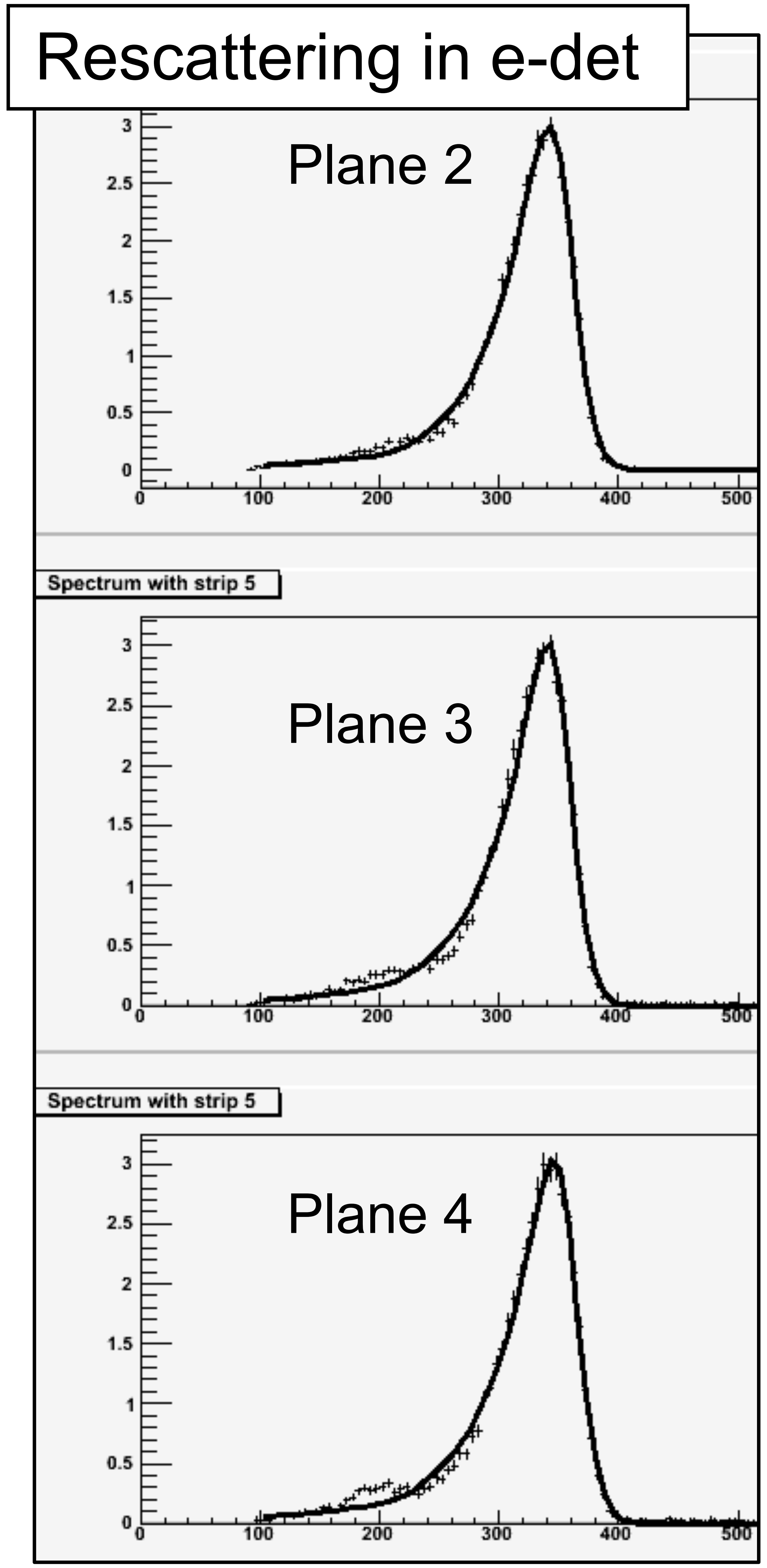
**HAPPEX-3 2009 (3 GeV)**



?!?

# HAPPEX-3 “bump”





**Lesson:** your electron response function may not be as pure as you would like. Test this, consider backgrounds created by Compton scattered events

# Lessons for Hall A (from Qweak)

**Important for electron detector to cover a large fraction of the Compton electron spectrum (include regions on both side of zero crossing).**

**Build DAQ simulation well before the experiment and use it to design and test a dead-time free and efficient DAQ.**

**Very important to collect data in event mode, scaler mode and accumulator mode, simultaneously.**

Dipangkar Dutta

More generally:  testing multiple ways of performing these measurements provide a catch for many otherwise-hidden sources of systematic errors.

But each independent test requires great attention to perform correctly - don’t do bad tests!

# Summary

- Other topics? There are many
  - Lots of work on laser polarimetry
  - Laser reliability issues may be addressed with hardware improvements.
  - Synchrotron light on photon detector and electron detector
  - ……

- Design of electron detector, photon detector, and DAQ need to be cognizant of specific needs of this measurement.
  - Both HVMAPS and diamond μstrips appear well suited, but the readout needs to match the needs of this measurement
  - DAQ design should come together so that there is time to simulate operation
  - Simulations of backgrounds, signals, and detector responses should be performed early enough to inform hardware, DAQ capabilities, and analysis
  - There is a lot of knowledge to build from, in publications, log entries, presentations, and institutional memory.  The key is to access it.

# Beam Aperture

Collimators protect optics at small crossing angles, but create backgrounds

Existing 1cm aperture (1.4° crossing)

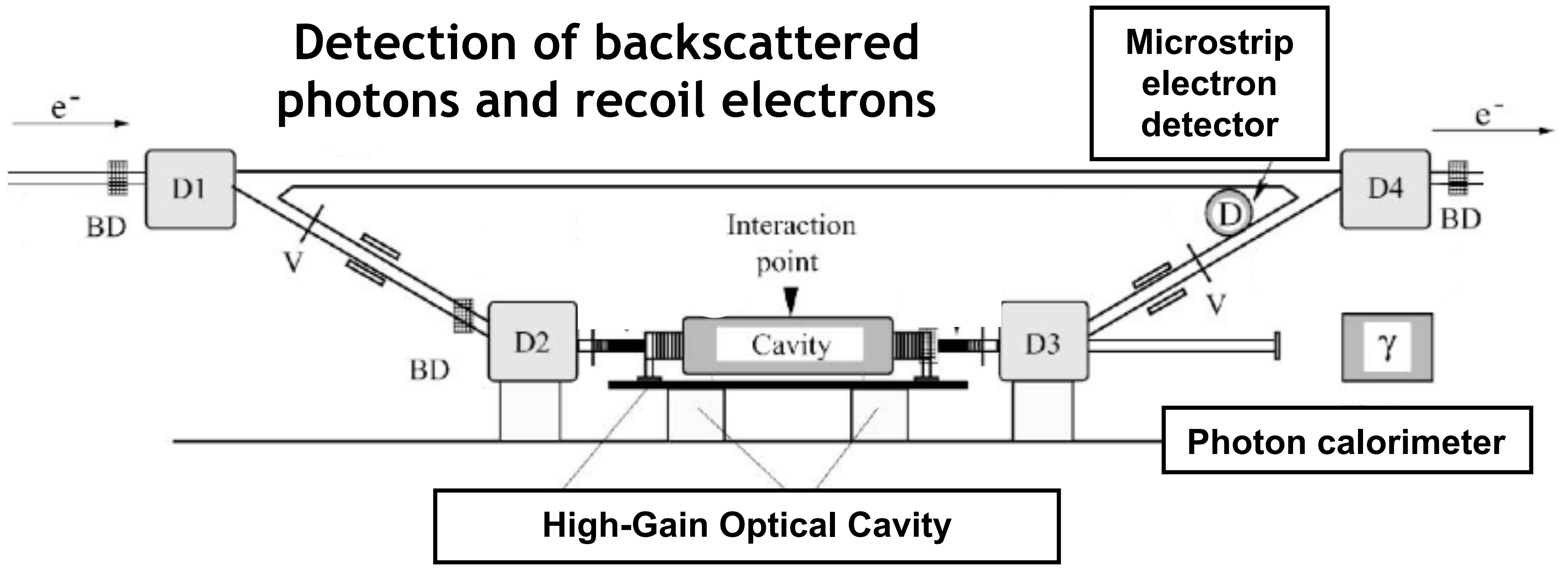
Typical “good” brem rate: ~ 100 Hz/uA
Residual gas should be about 10x less

# Basic Strategy

- Two independent measurements in the experimental hall which can be cross-checked
- Continuous monitoring during production (protects against drifts, precession…)
- Statistical power to facilitate cross-normalization (get to systematics limit in about 1 hour)

## Compton

- Polarized electron-photon scattering
- continuous measurement with high precision
- state-of-the-art: 0.6% precision at JLAB at 1 GeV



**Detection of backscattered photons and recoil electrons**

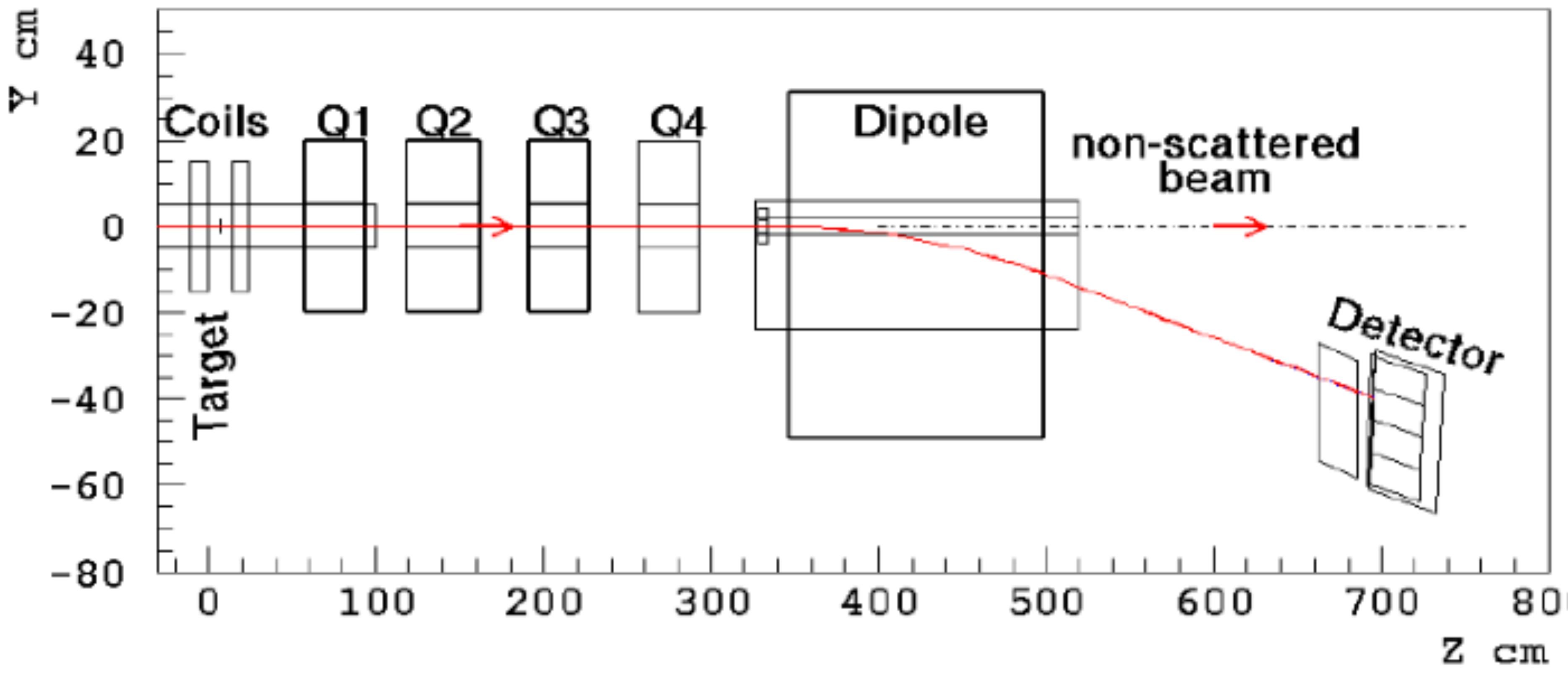
**Microstrip electron detector**

**Photon calorimeter**

**High-Gain Optical Cavity**

## Møller

- Elastic *ee* scattering from magnetized iron target
- 0.5% precision demonstrated with Hall C polarimeter

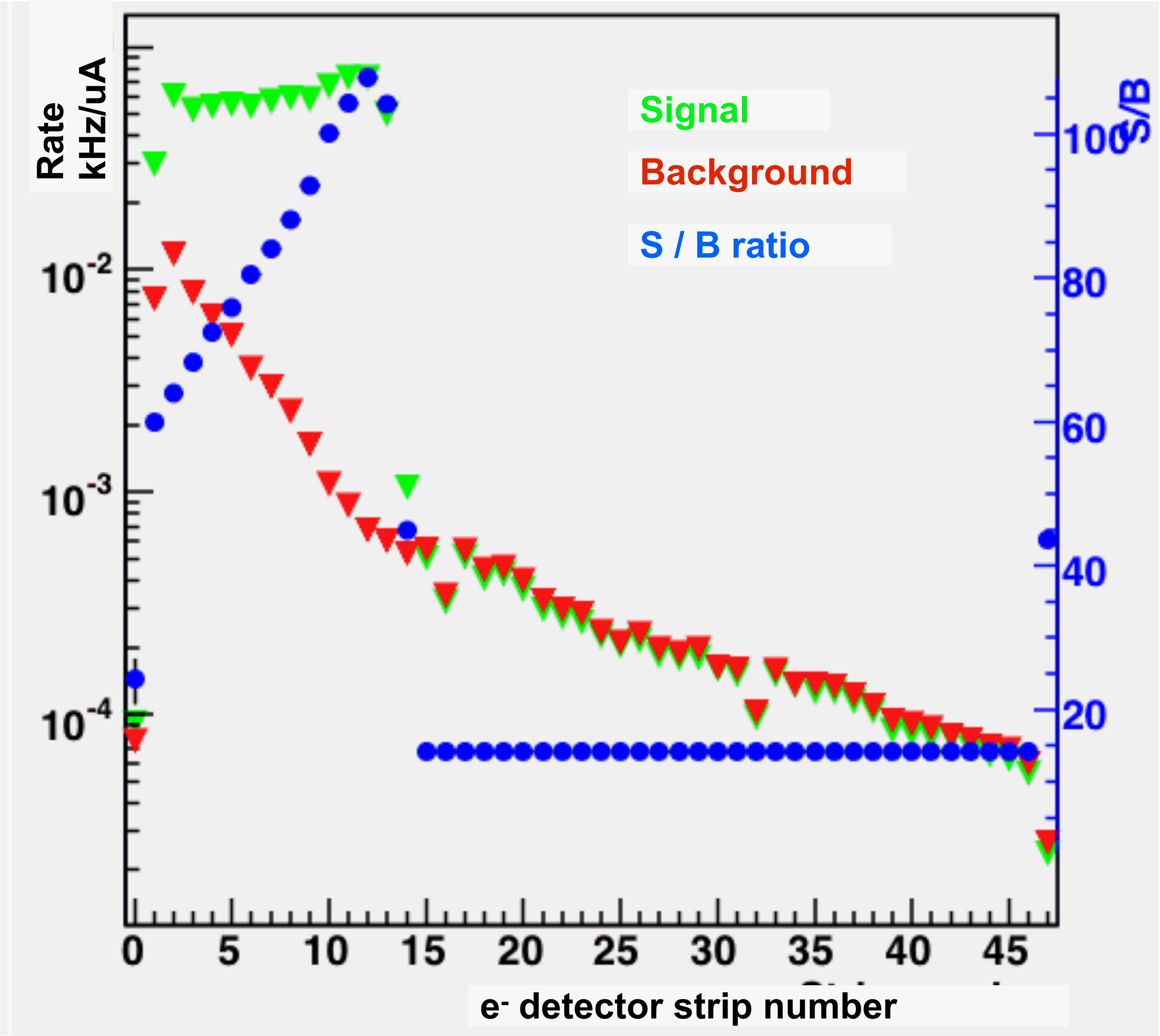


**Achieving ultimate precision requires cross-checks and study**

- ultimate precision will only be achieved during the long MOLLER run

| | |
|---|---|
| • Phase 1: | 1% |
| • Phases 2 and 3: | 0.4% |

# Electron Detector in Hall A (2005)

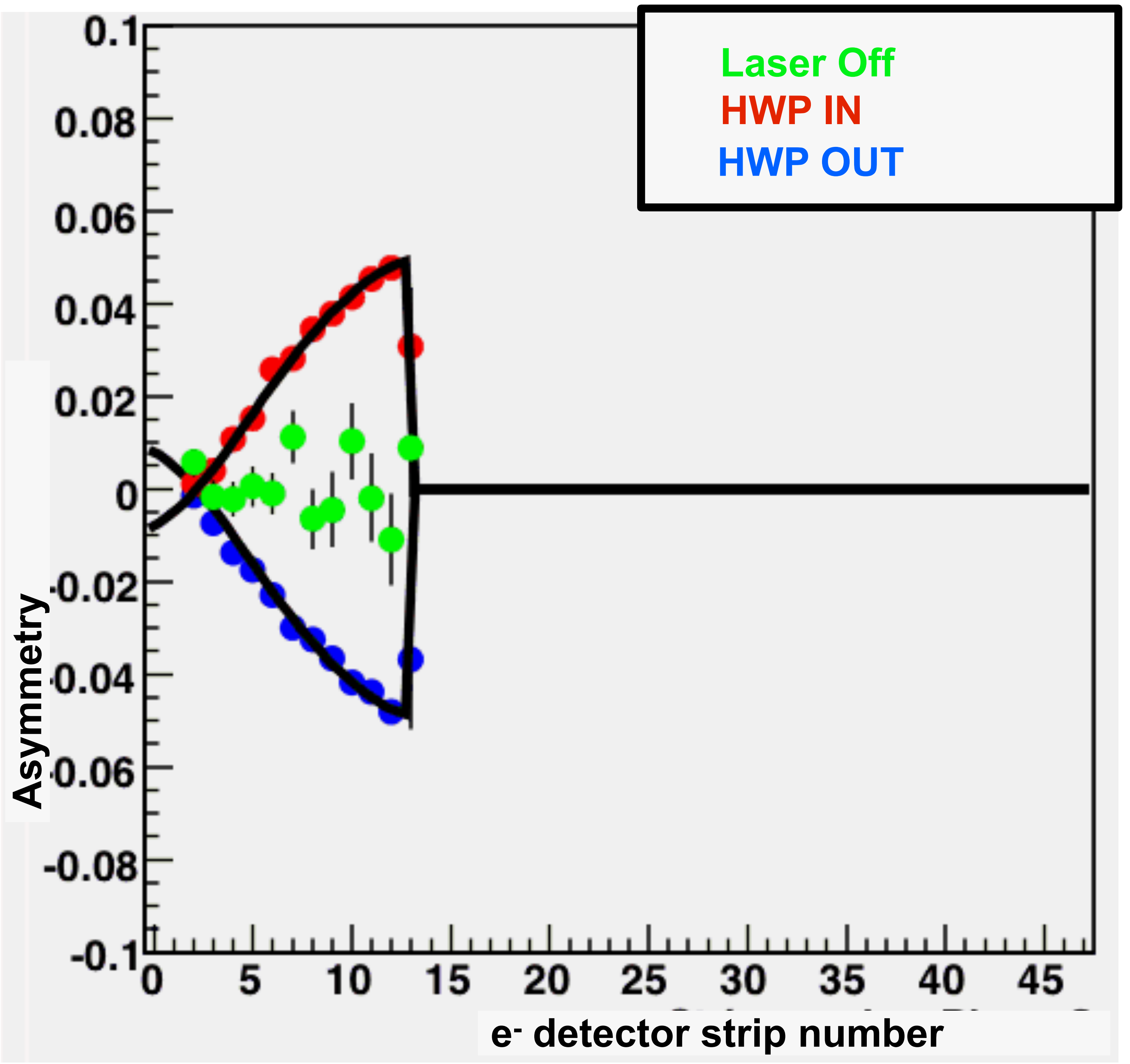


data from HAPPEX-II (2005)

$E_{beam}$~3 GeV, 45 uA,

$P_{cavity}$ < 1000 W

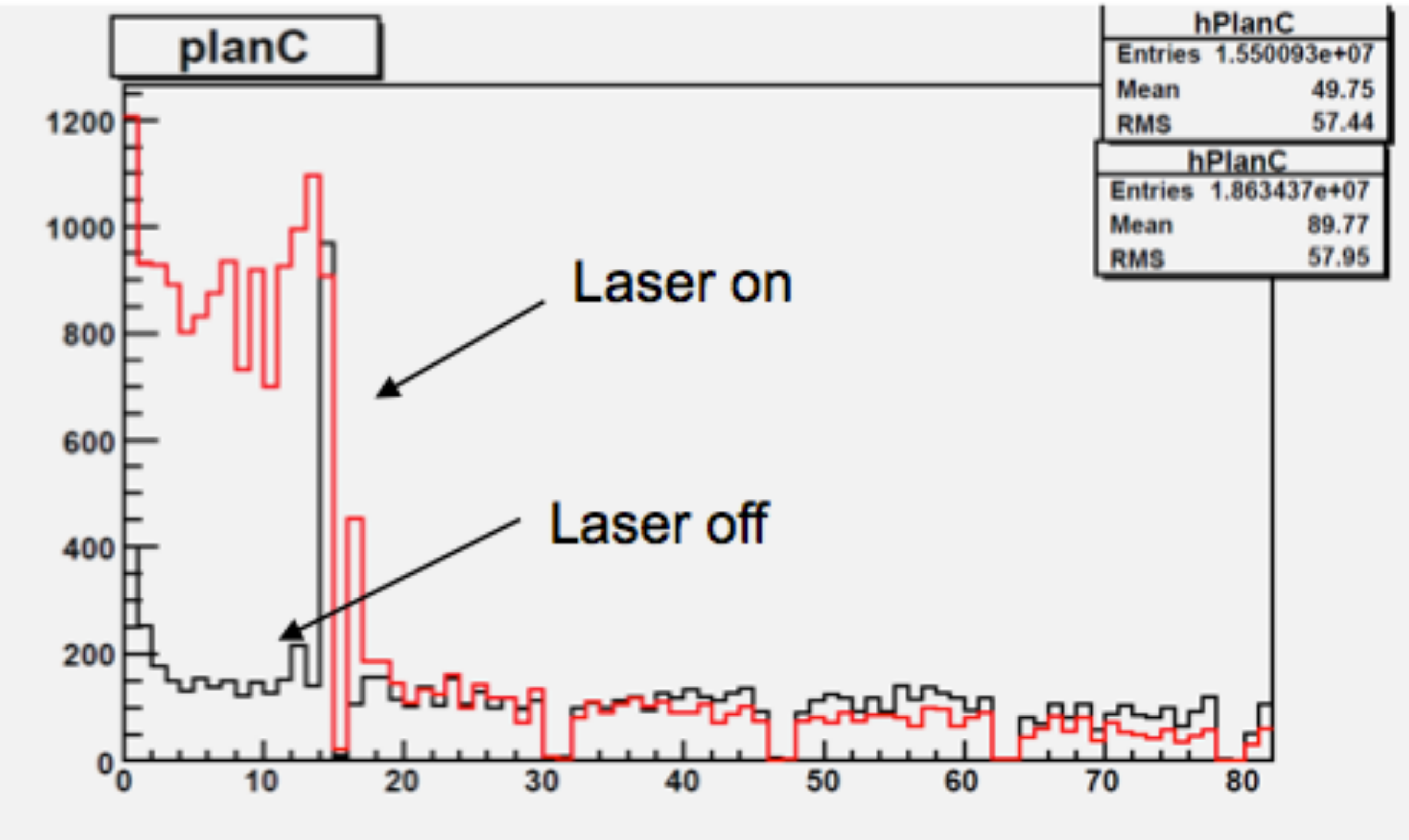
Background ~ 100 Hz / uA at $Y_{det}$ ~ 5mm



# Current Electron μstrip Detectors

## Noise vs. signal, especially in Hall, makes high efficiency hard

### Existing Hall A Si strip system



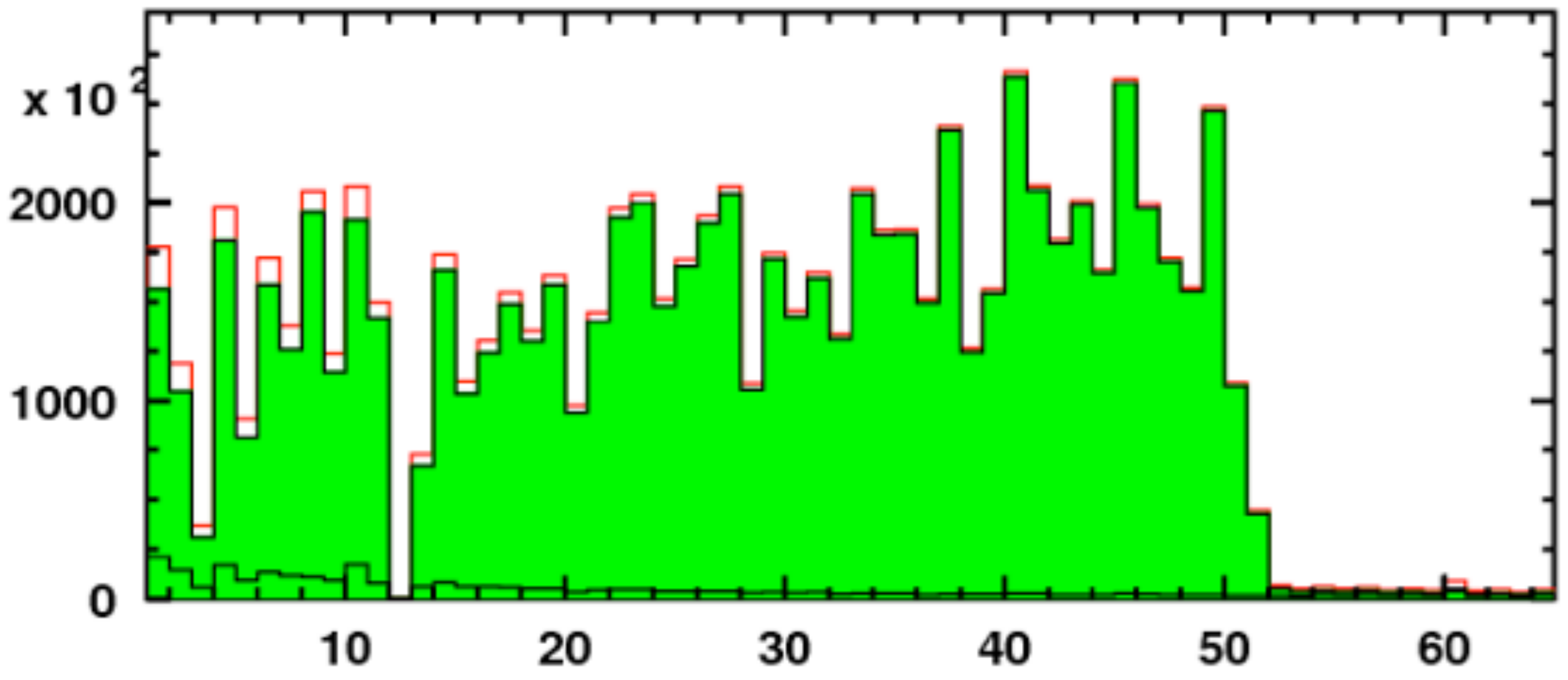
Thicker Si strips with existing electronics? (is rescattering from Si substrate an important systematic correction?)

New electronics for Si ustrips?

Cons: radiation hardness and synch light sensitivity

### Hall C Diamond strips

Rough guess: 65% efficient?



Hall C style diamond strips?

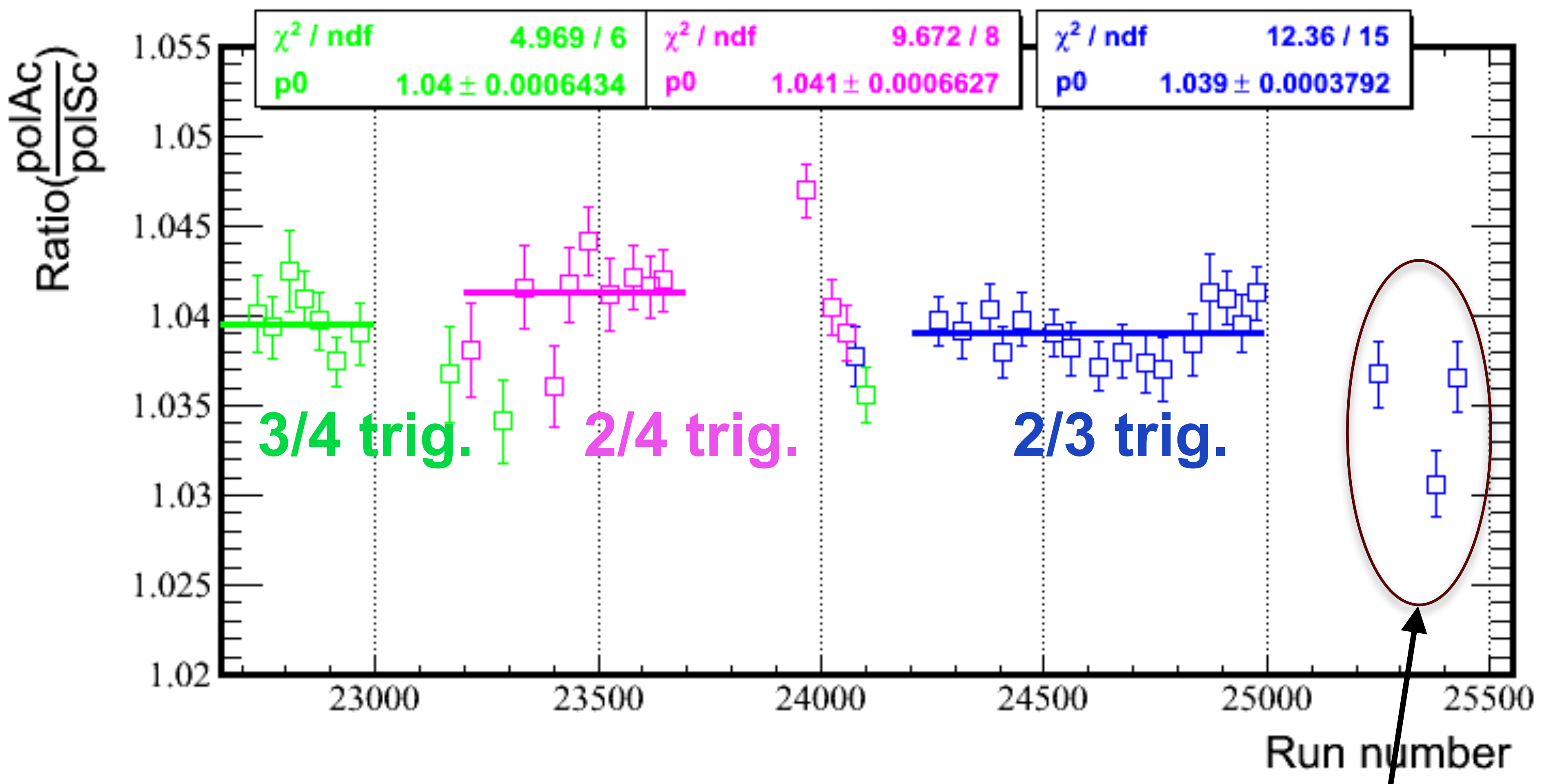
Improved electronics? (compton edge from hit pattern is an important calibration point: high efficiency needed!)

Improved radiation hardness & synch light sensitivity

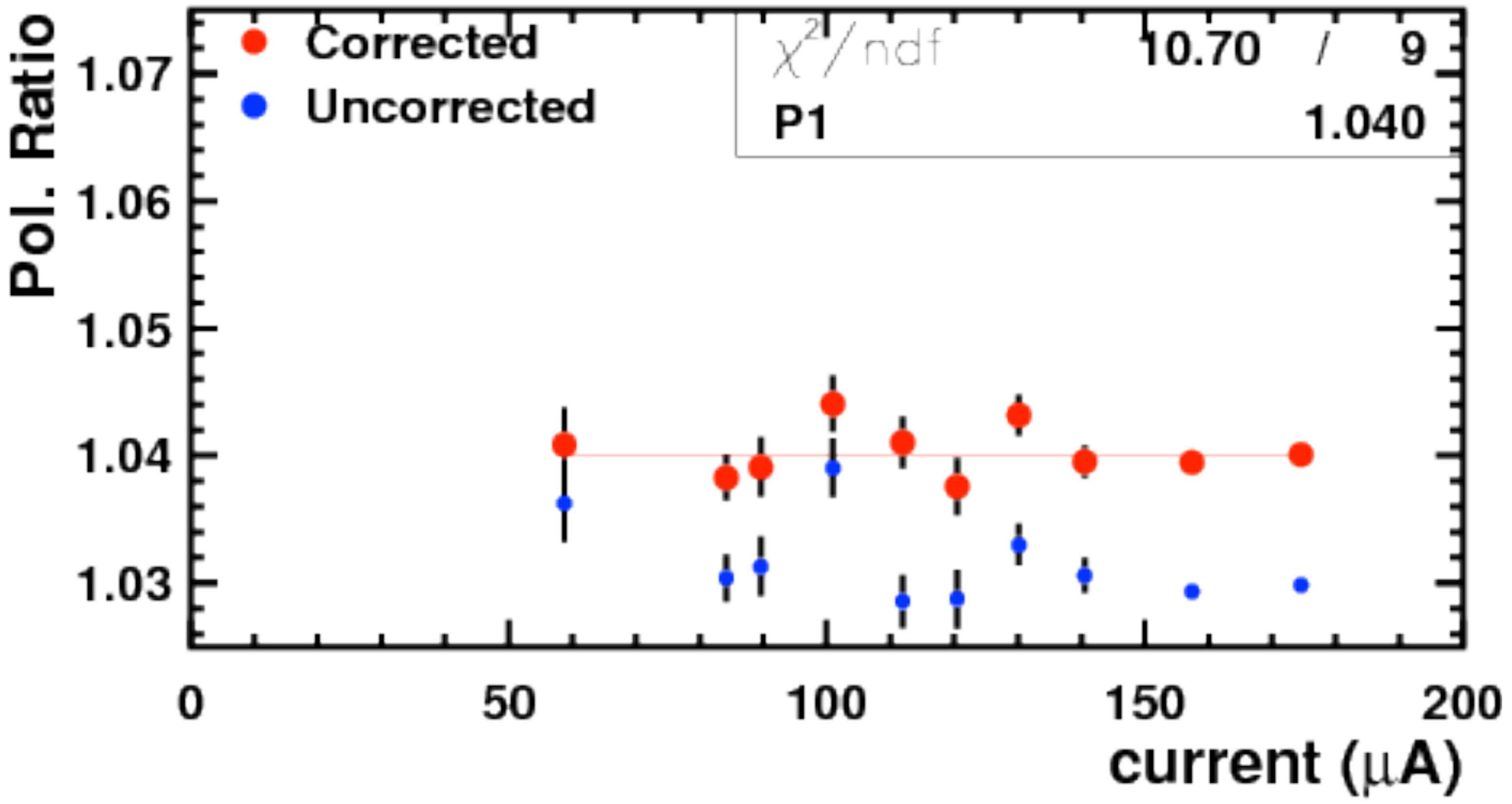
# Scaler/Accum Polarization Ratio

## A Powerful diagnostic

If trigger inefficiency corrections, background subtractions, noise subtraction and other procedures are implemented correctly - the ratio of the polarization from scaler to accumulator data should remain constant.



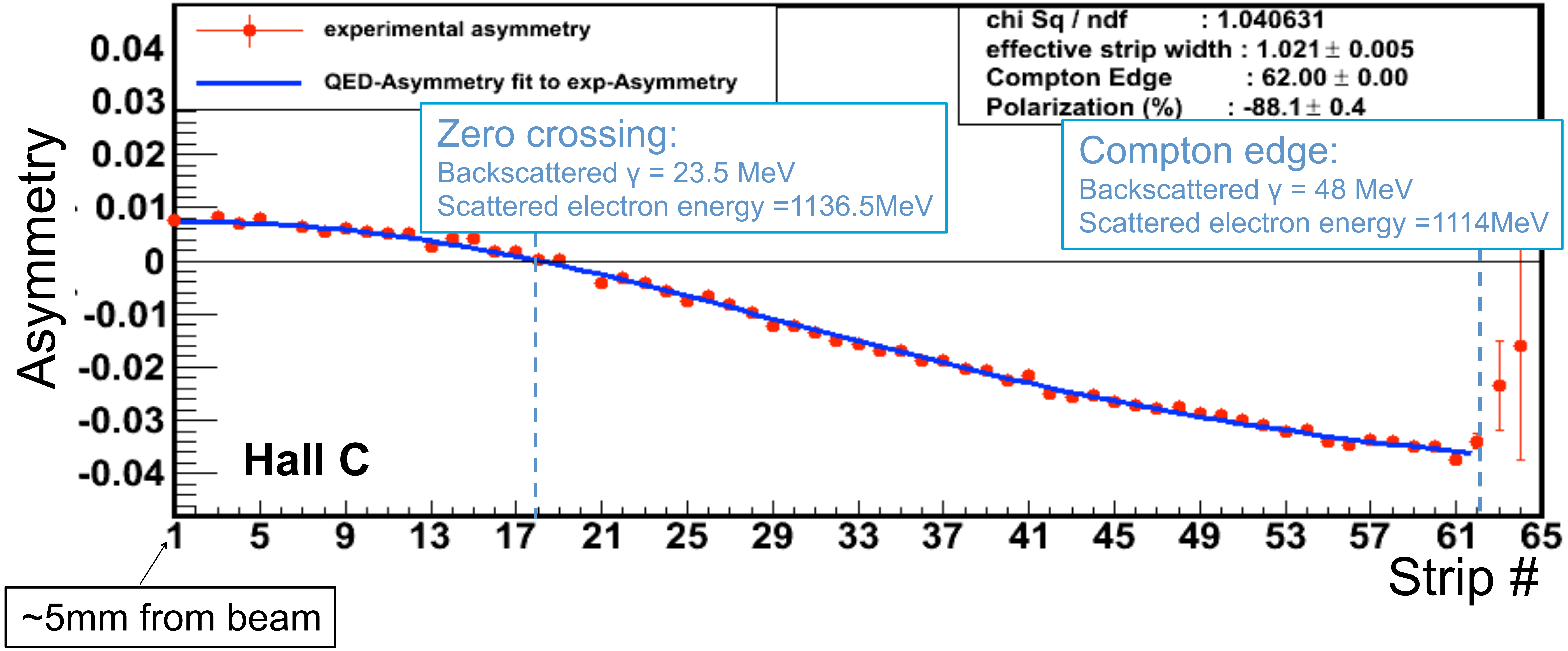
All runs in clusters of 30 runs



The average deviation of 0.3% is assigned as the systematic uncertainty of the inefficiency correction. An additional 0.3% point-to-point uncertainty is also included

Variation of vertical beam angle within a run seems to be the likely cause

# Electron Detector, Hall C



Zero crossing:
Backscattered γ = 23.5 MeV
Scattered electron energy =1136.5MeV

Compton edge:
Backscattered γ = 48 MeV
Scattered electron energy =1114MeV

~5mm from beam

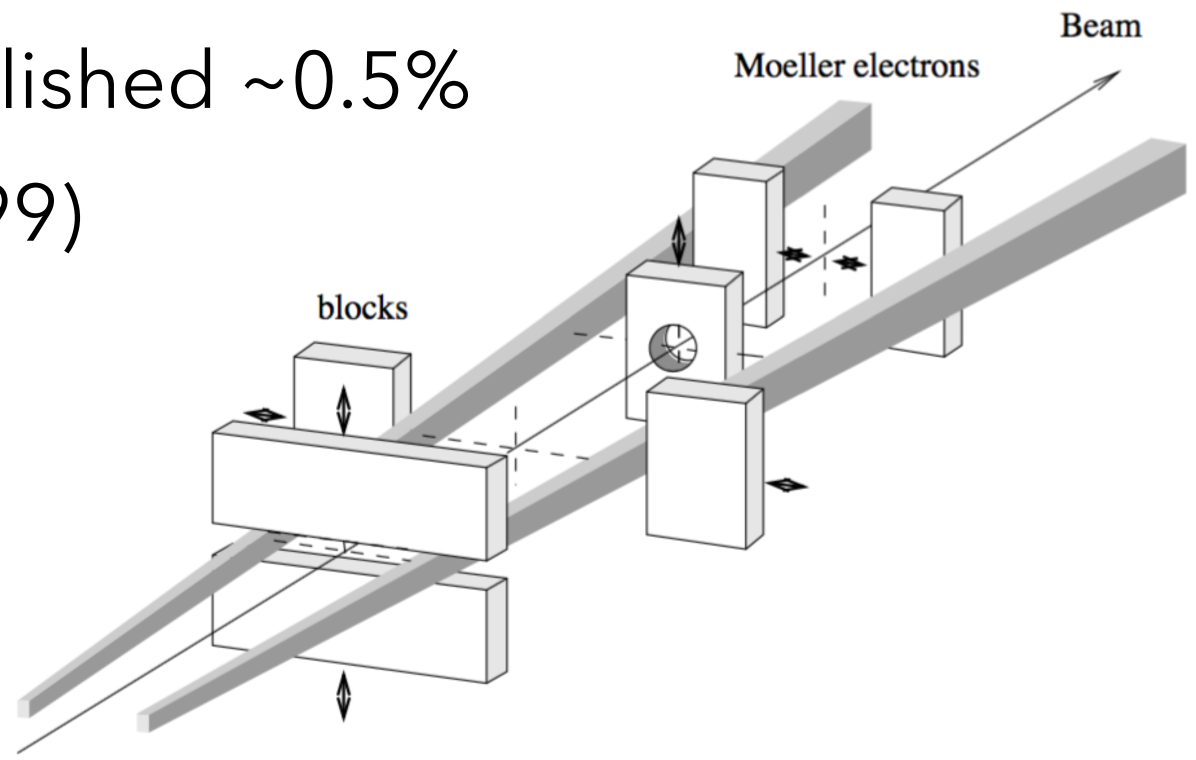
- Fit to the asymmetry spectrum shape to theoretical asymmetry distribution.
- Shape (including zero crossing) provides calibration, to absolute asymmetry.
- Check with Compton edge in the rate spectrum, and known BdL.

# High Precision Polarimetry = Long Term Program

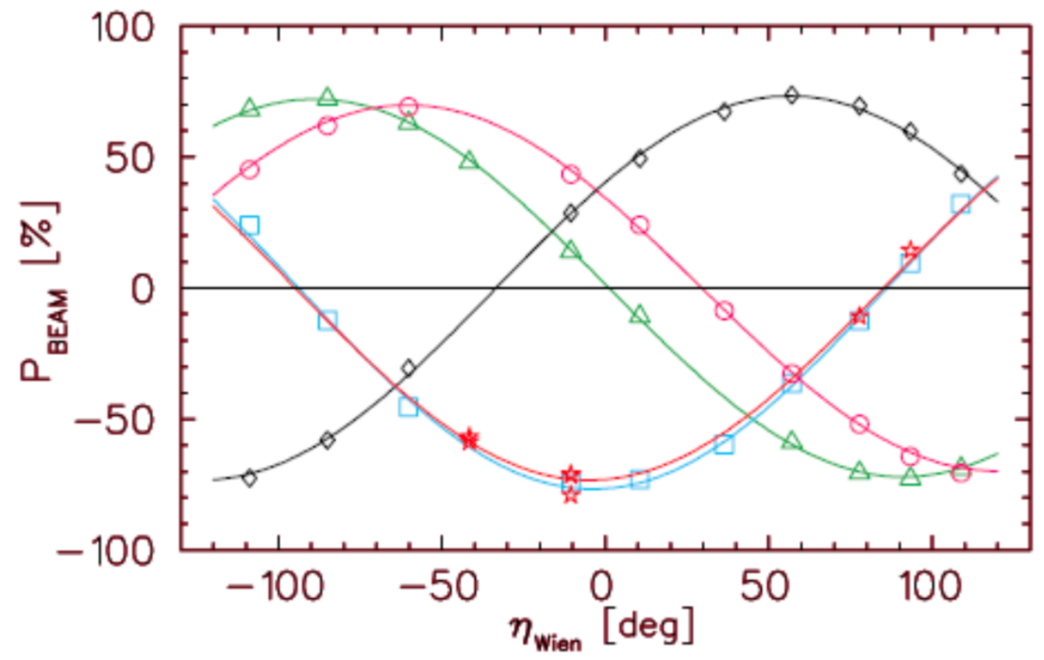
**Hall C Moller**

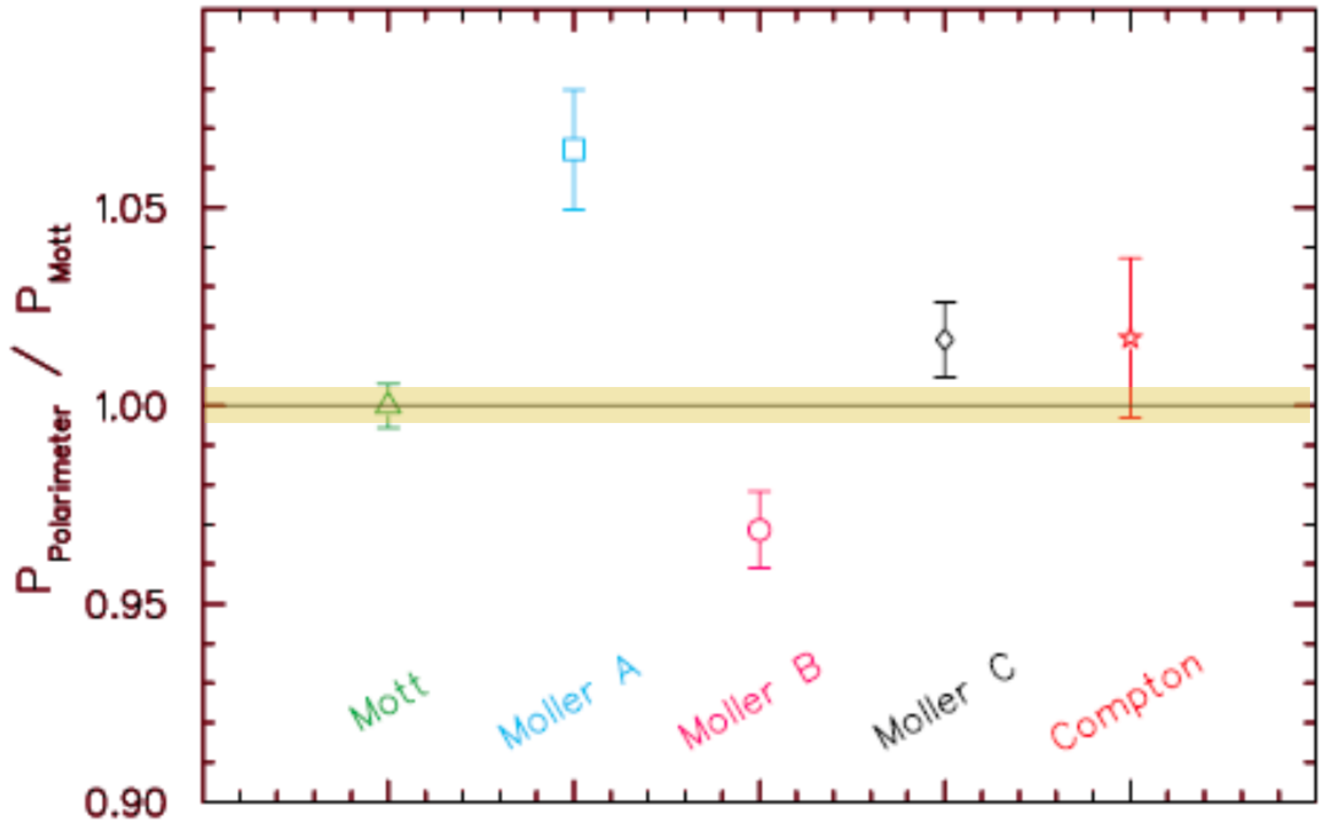
published ~0.5%

(1999)



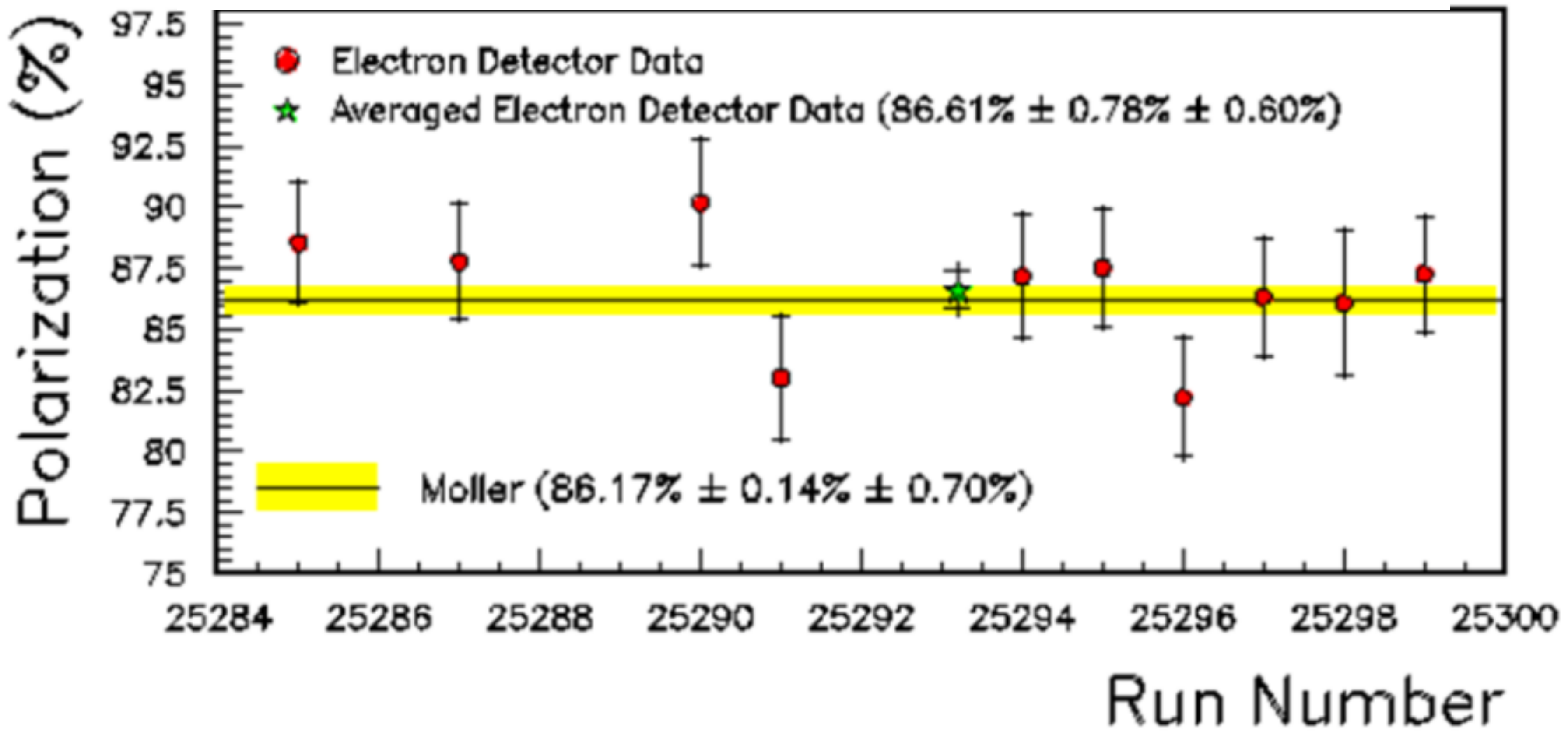
**Spin Dance** (2004)





| | | | |
|---|---|---|---|
| **HAPPEX-3** (2009) | 3 GeV | Integrating Photon | 1% |
| **PREX-I** (2010) | 1 GeV | Integrating Photon / High-Field Moller | 1% |
| **Qweak** (2010-12) | 1 GeV | Compton Electron / High- | 0.6%/ 0.85% |

**Qweak Moller-Compton-Moller (2012)**



| | |
|---|---|
| **PREX-II / CREX** (planned 2019) | High-field Moller to 1%, Compton to 1% at 1-2 GeV |

**SOLID-PVDIS** Must have 0.4% precision

**High Precision Polarimetry ad-hoc Working Group meeting, November 2016**

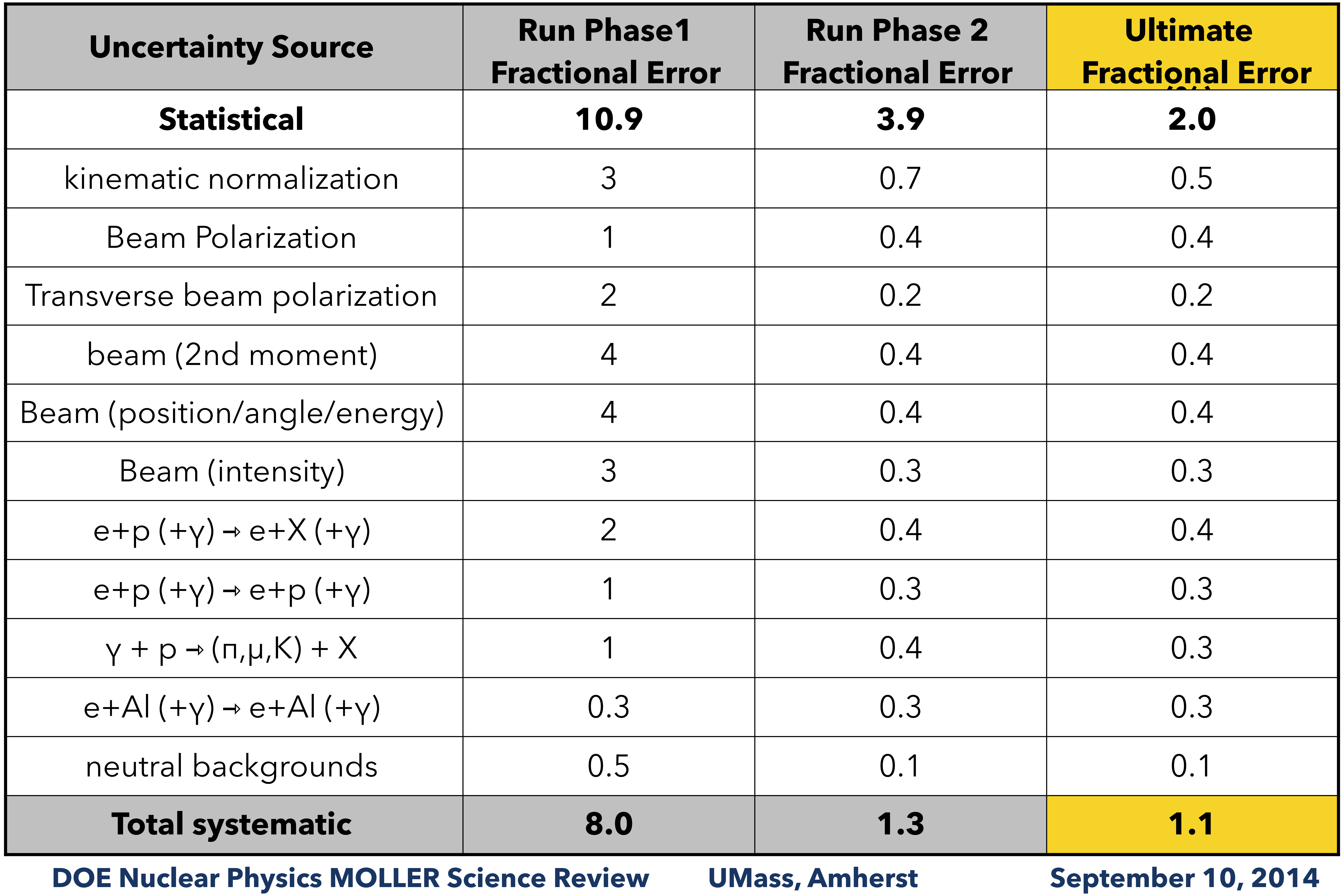
30 attendees from 10 institutions, discussing Mott, and Hall A Moller and Compton

Precision electron beam polarimetry for next generation nuclear physics experiments

K. Aulenbacher, E. Chudakov, **D. Gaskell**, J. Grames, and K. Paschke

Intl J of Mod Phys E Vol. 27, No. 7 (2018) 1830004

# Summary of Systematic Uncertainty, run phases



| Uncertainty Source | Run Phase1 Fractional Error | Run Phase 2 Fractional Error | Ultimate Fractional Error |
|---|---|---|---|
| **Statistical** | **10.9** | **3.9** | **2.0** |
| kinematic normalization | 3 | 0.7 | 0.5 |
| Beam Polarization | 1 | 0.4 | 0.4 |
| Transverse beam polarization | 2 | 0.2 | 0.2 |
| beam (2nd moment) | 4 | 0.4 | 0.4 |
| Beam (position/angle/energy) | 4 | 0.4 | 0.4 |
| Beam (intensity) | 3 | 0.3 | 0.3 |
| e+p (+γ) → e+X (+γ) | 2 | 0.4 | 0.4 |
| e+p (+γ) → e+p (+γ) | 1 | 0.3 | 0.3 |
| γ + p → (π,μ,K) + X | 1 | 0.4 | 0.3 |
| e+Al (+γ) → e+Al (+γ) | 0.3 | 0.3 | 0.3 |
| neutral backgrounds | 0.5 | 0.1 | 0.1 |
| **Total systematic** | **8.0** | **1.3** | **1.1** |

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# Mott polarimetry

Wasn’t featured in the proposal, but useful and important tool and cross-check

- Measurement at low energy in injector
- Upgraded for precise asymmetry measurement
- Techniques for limiting Sherman function uncertainty
- Ongoing research into AESOP using atomic optical techniques to calibrate Mott Sherman function (T. Gay, Nebraska)

# Ultimate Systematic Uncertainties

Estimates of achievable uncertainties
based on previous experience, with modest extrapolation

## Moller polarimeter

| Relative Error (%) | |
|---|---|
| Target polarization | 0.30% |
| Analyzing power | 0.20% |
| Levchuk effect | 0.20% |
| Target Temperature | 0.05% |
| Dead time | 0.10% |
| Background | 0.01% |
| Others | 0.10% |
| Total | 0.45% |

## Compton polarimeter

| Relative Error (%) | **electron** | **photon** |
|---|---|---|
| Position Asymmetries | - | |
| $E_{beam}$ and $\lambda_{laser}$ | 0.03 | |
| Radiative Corrections | 0.05 | |
| Laser Polarization | 0.2 | |
| Background/Deadtime/ | 0.2 | 0.2 |
| Analyzing Power Calibration / Detector Linearity | 0.25 | 0.35 |
| Total | 0.38 | 0.45 |

⬜ correlated

🟩 uncorrelated

MOLLER polarimetry precision goal
- Phase 1: 1%
- Phases 2 and 3: 0.4%