Electron Beam Polarimetry

Experience from HERA
& Design Ideas for EIC

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EIC Meeting Stony Brook
January 10-12, 2010

Massachusetts Institute of Technology

University of Michigan

Thanks to Wolfgang Lorenzon and Avetik Airapetian for several figures and slides

Overview

- Electron beam polarimetry: **Møller** and **Compton**
- Electron polarimetry at **HERA**
  - Spin physics at HERMES, H1 and Zeus
  - Transverse polarimeter (TPOL)
  - Longitudinal polarimeter (LPOL)
  - Cavity polarimeter upgrade
- Electron polarimetry at **EIC**
  - Hybrid technique: simultaneous counting and integration
  - Møller polarimetry on polarized atomic hydrogen
- Summary

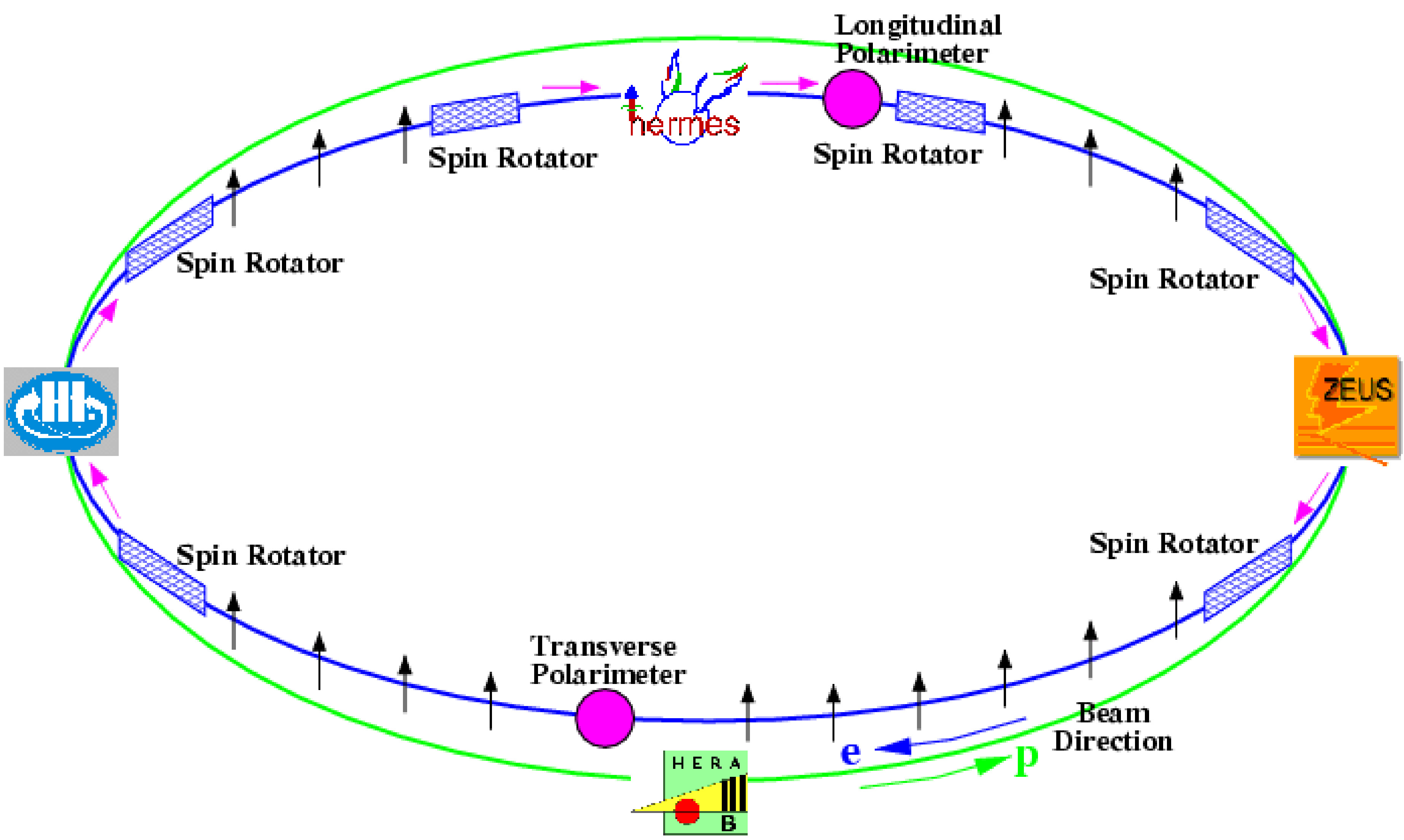
Electron Beam Polarimetry

- Techniques currently in common use:
  - **Mott scattering**: electron on nucleus
    - Spin-orbit coupling of electrons (< few MeV) with target nucleus
  - **Møller (Bhabha) scattering**: electron/positron on electrons
    - Atomic electrons in Fe(-alloy), polarized by external magnetic field
  - **Compton scattering**: electron/positron on photons
    - Laser photons scatter off the lepton beam (> 1 GeV)
- Precision achieved or set as goal:
  - $\Delta P/P \approx 2\%$ (HERA: 3.1% TPOL, 1.6% LPOL)
  - $\Delta P/P \approx 1\%$ (Hall C, EIC)
  - $\Delta P/P \approx 0.25$–0.10% (ILC), rather ambitious...

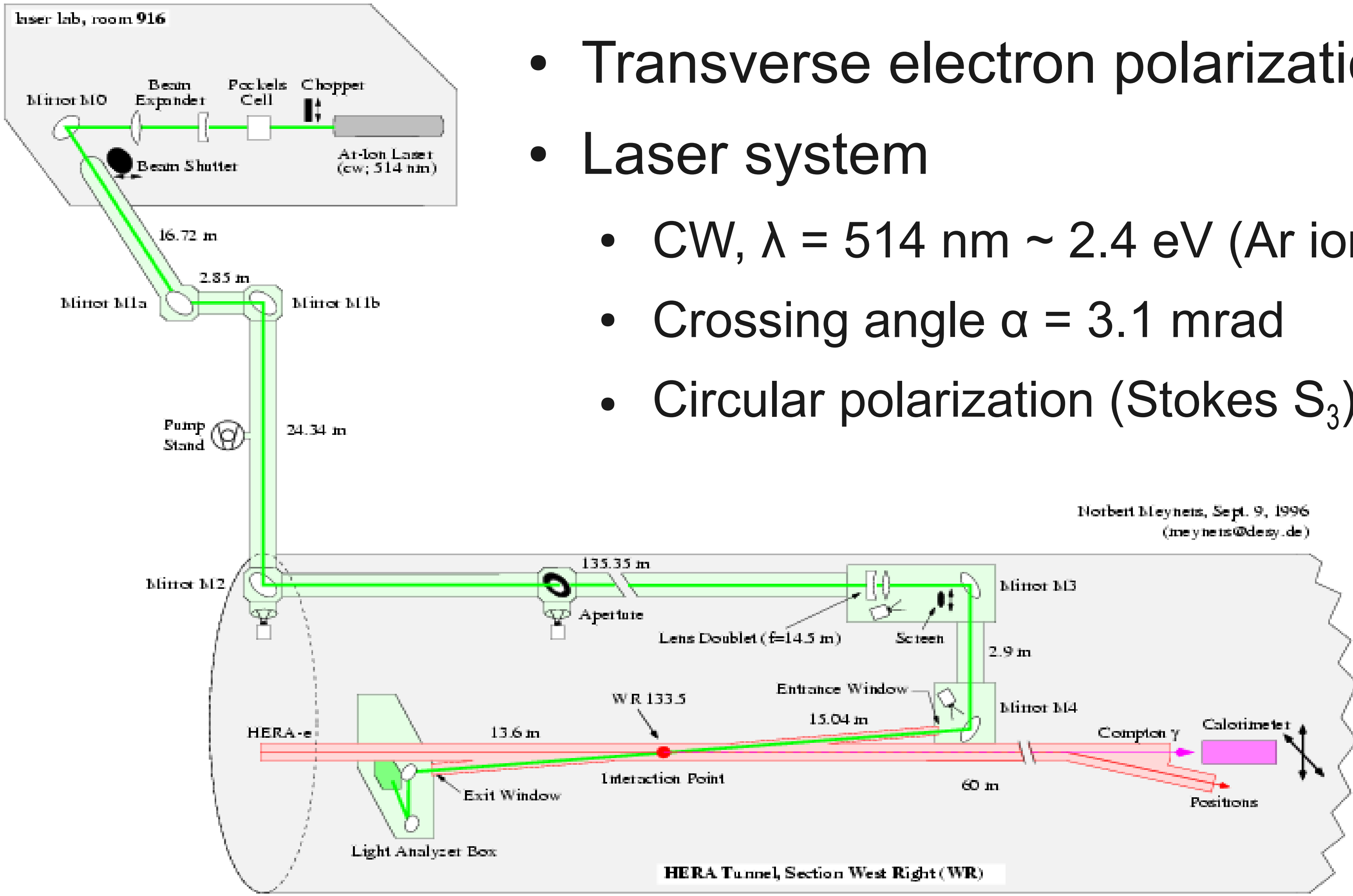
Electron Beam Polarimetry

- **Mott polarimeters**: destructive, only at low energy
- **Møller/Bhabha polarimeters**
  - Destructive, hence only intermittent measurements
- Systematics
  - Target polarization
  - Target heating destroys polarization → low current
  - Levchuk effect: K-shell
  - High-current extrapolation
- **Compton polarimeters**
  - Continuous, non-invasive
  - High statistical precision
- Systematics
  - Laser circular polarization
  - Response of calorimeter in counting mode
  - Analyzing power in integrating mode

Electron Polarimetry at HERA



Transverse Polarimeter (TPOL)



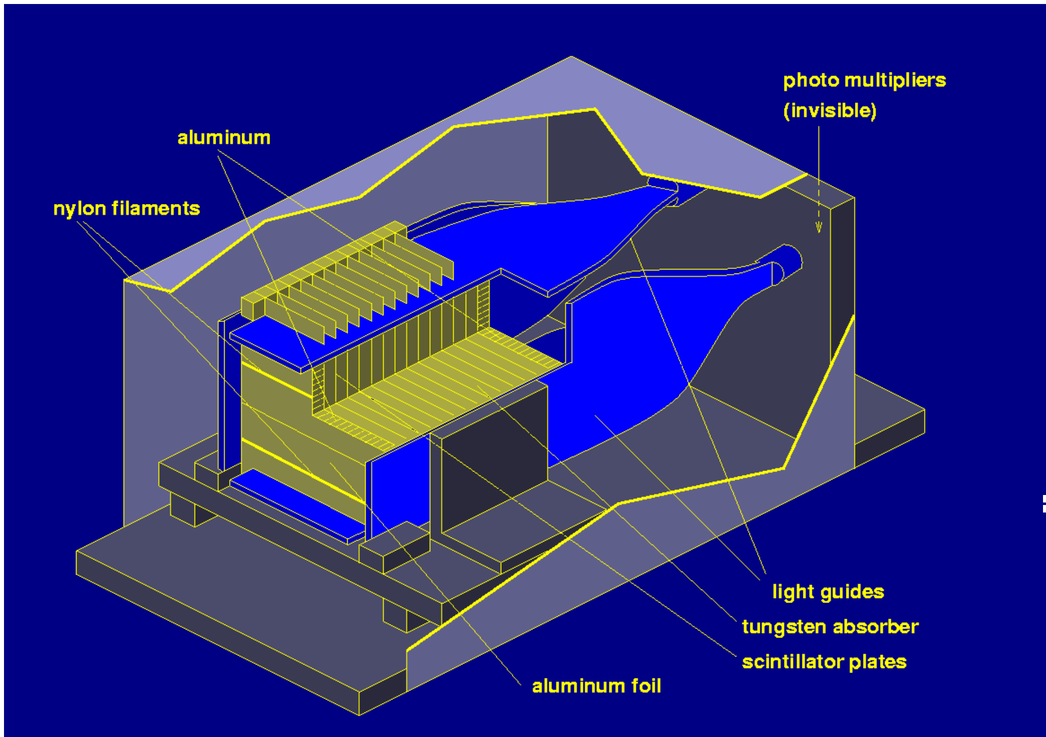
- Transverse electron polarization
- Laser system
  - CW, λ = 514 nm ~ 2.4 eV (Ar ion)
  - Crossing angle α = 3.1 mrad
  - Circular polarization (Stokes S_3)

Transverse Polarimeter (TPOL)

$$\frac{d^2\sigma}{dE\,d\phi} = \Sigma_0(E) + S_1\Sigma_1(E)\cos 2\phi + S_3(P_Y\Sigma_{2Y}(E)\sin\phi + P_Z\Sigma_{2Z}(E))$$

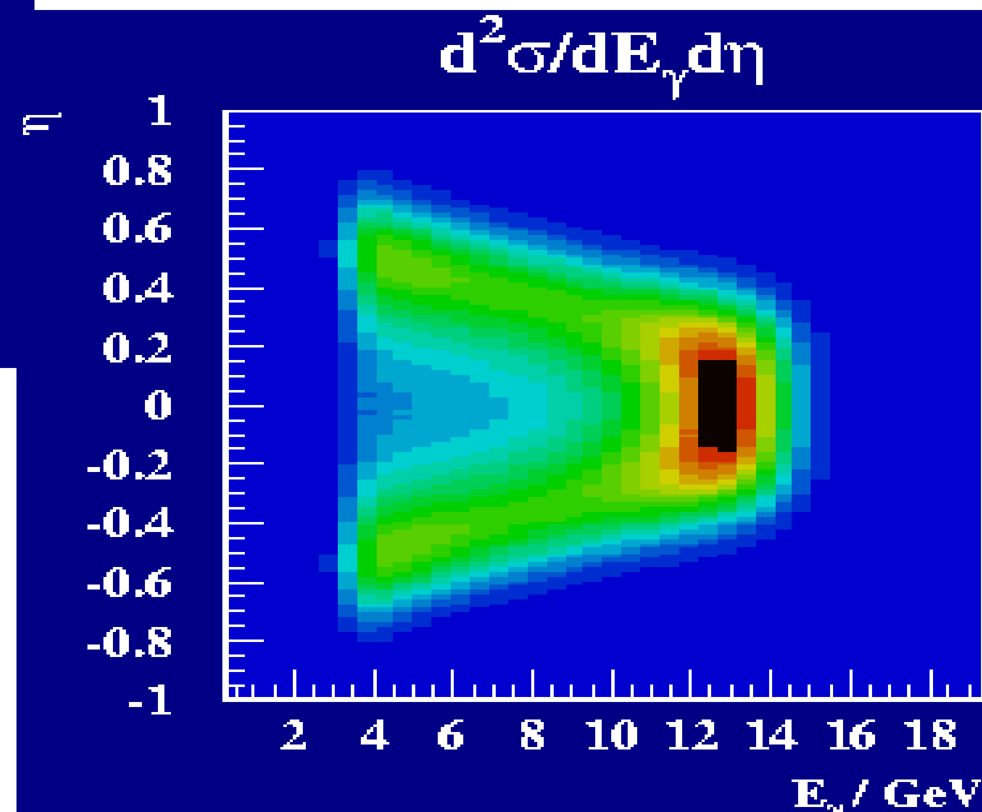
- Angular asymmetry in Compton cross section
  - Very small **up/down asymmetry** (even at 65m throw)
  - Precise position measurement needed (< 10μm)
  - Need to know distance between IP and detector, equivalent to beam positions at IP (small crossing angle)
- Top/bottom segmented sampling calorimeter
  - Tungsten/plastic scintillator plates, wavelength shifters
  - 4 PMT channels: up, down, left, right
  - Segmented in top/bottom half: up, down channels

Transverse Polarimeter (TPOL)



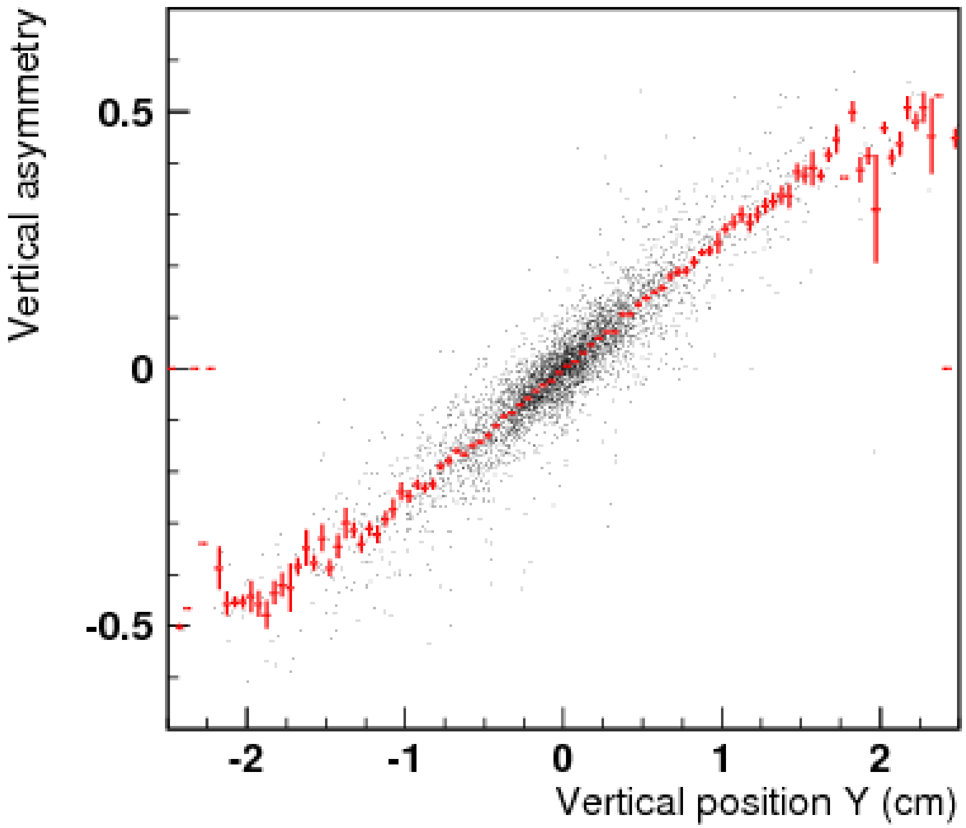
- Vertical asymmetry η

$$\eta = (E_{up}-E_{down}) / (E_{up}+E_{down})$$



- Main uncertainty in y(η) transformation
- Si strip detector for direct measurement of y(η)

Transverse Polarimeter (TPOL)



- Main systematics TPOL
  - Transformation from energy top/bottom asymmetry η to position y
  - Location of IP is very dependent on exact beam position and linear with A
  - Linear polarization components in laser cause additional asymmetry
  - Total = 3.1%

Longitudinal Polarimeter (LPOL)

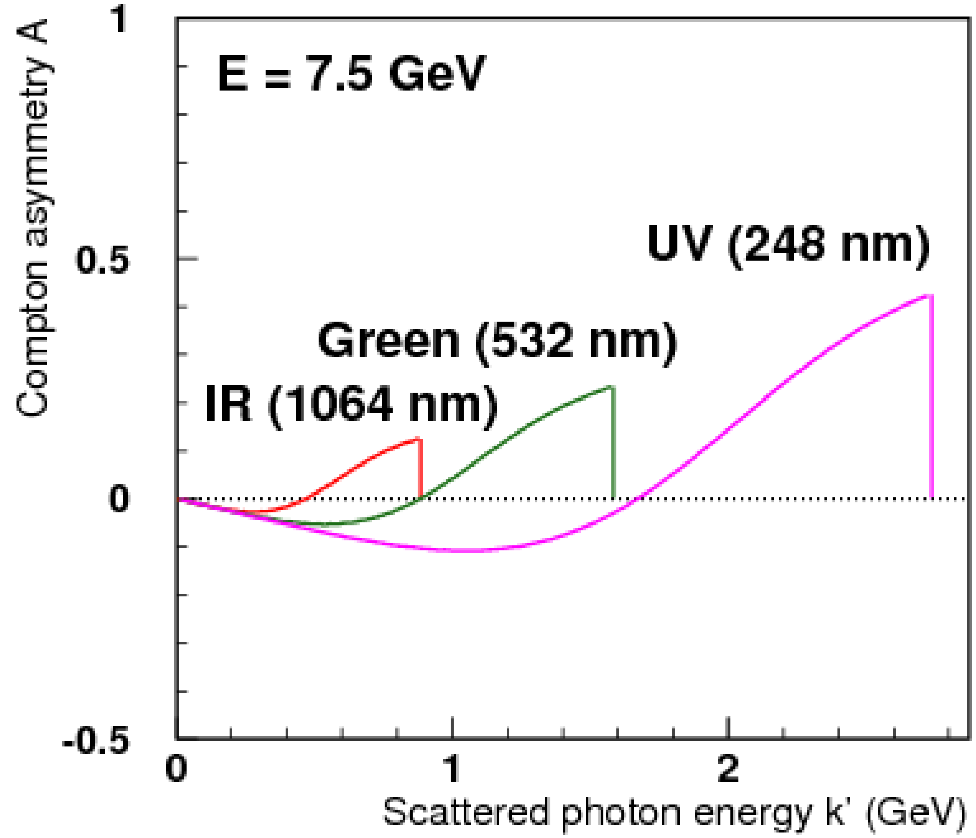
- Longitudinal polarization between spin rotators
- Energy asymmetry in Compton scattering cross section

$$\frac{d\sigma}{dE_\gamma} = \frac{d\sigma_0}{dE_\gamma}\left[1 + P_e P_\lambda A_z(E_\gamma)\right]$$

- Energy asymmetry measurement used in virtually all current Compton polarimeter systems
- But two distinct measurement techniques

Compton Polarimetry

- **Single photon mode** measure energy of every Compton photon
- Highest photon energy: Compton edge ~ $k \cdot E^2$
- Highest asymmetry (at Compton edge) ~ $k \cdot E$
- Zero-crossing and Compton edge as calibration points



- **Integration mode**: accumulation of Compton photons

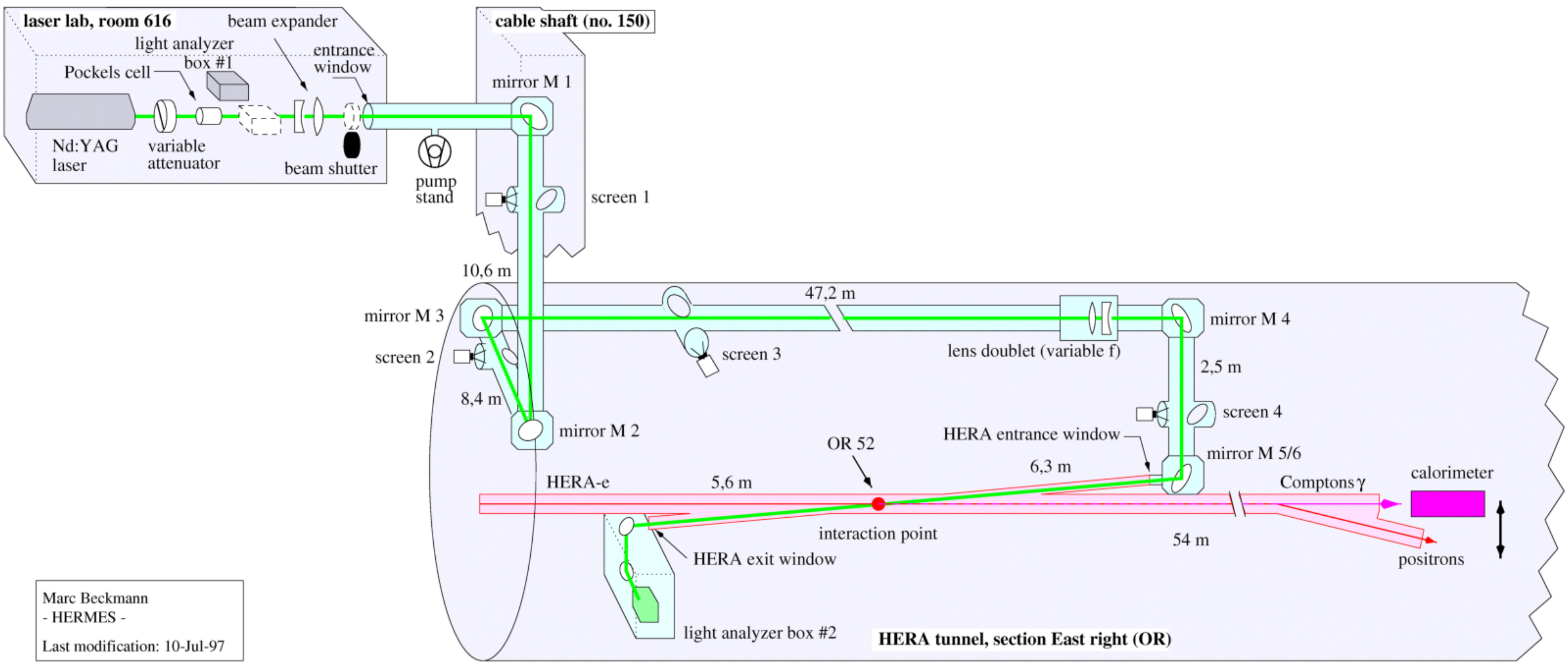
Compton Polarimetry

- **Single photon mode**
  - One or very few Compton photons per time window
- Advantages
  - Unambiguous view on physical processes
- Disadvantages
  - Sensitive to calorimeter scale (Compton edge)
  - Inherently lower rate: differential cross section

- **Integration mode**
  - Many Compton photons, in short time window
- Advantages
  - Bremsstrahlung basically not background anymore
  - Independent of absolute energy calibration (robust)
- Disadvantages
  - No easy monitoring of calorimeter possible

Longitudinal Polarimeter (LPOL)

- Integration mode: few hundred photons per event
- Laser system: 100 Hz pulsed, 200 mJ/pulse, 532 nm



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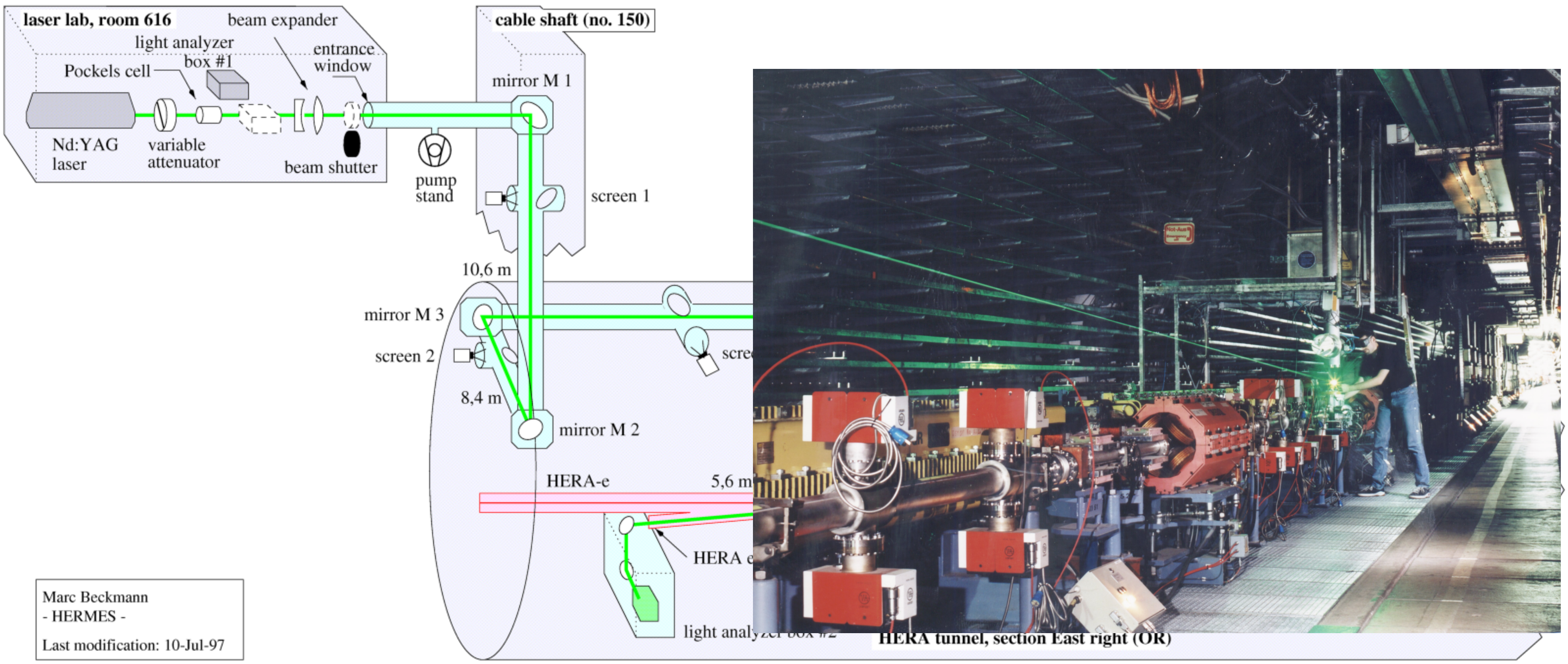

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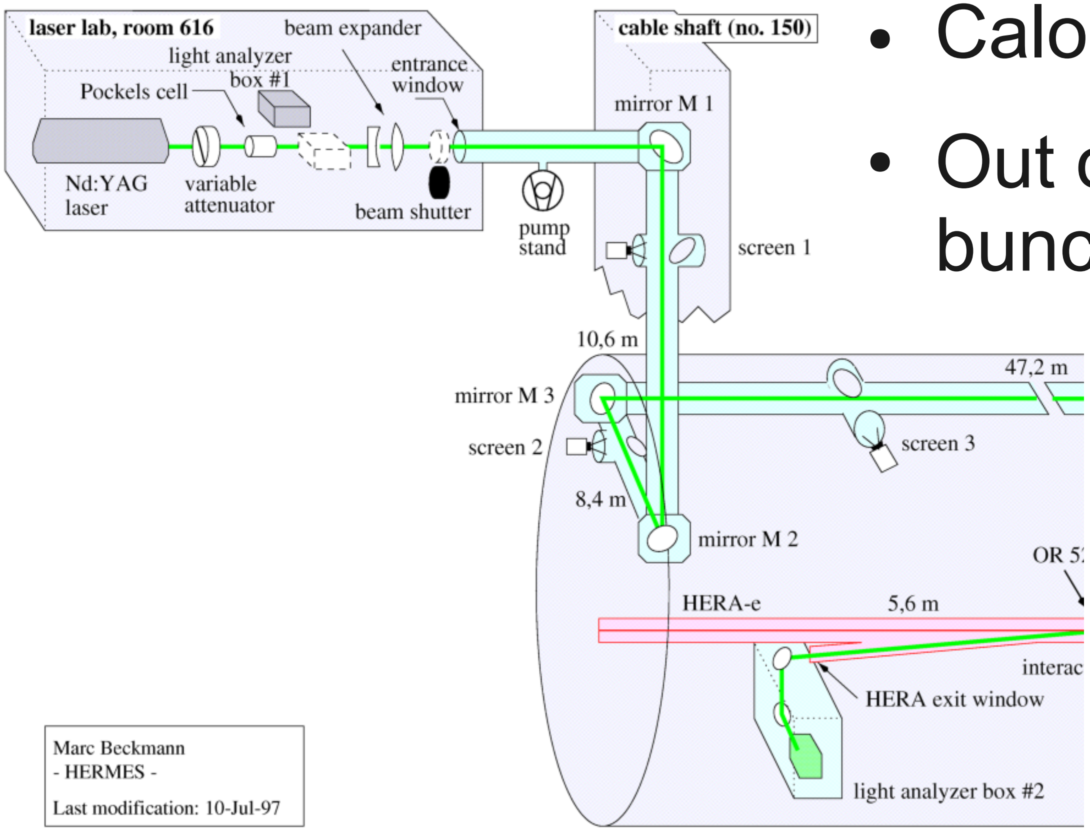
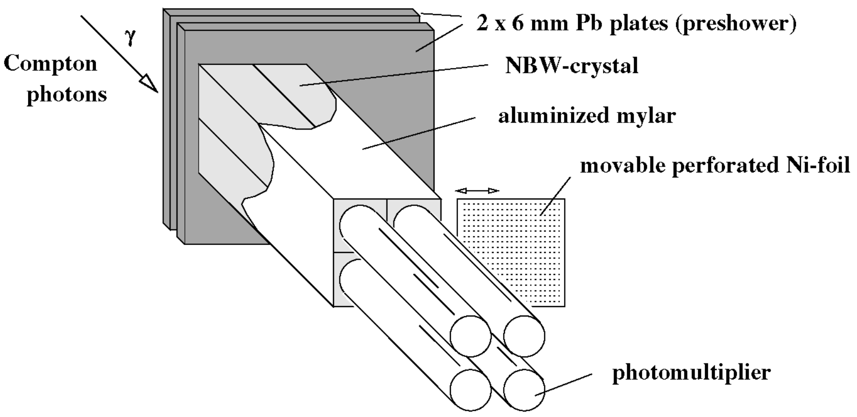


- Calorimeter: 4 × $NaBi(W0_4)_2$
- Out of gate, pulses between bunches → background



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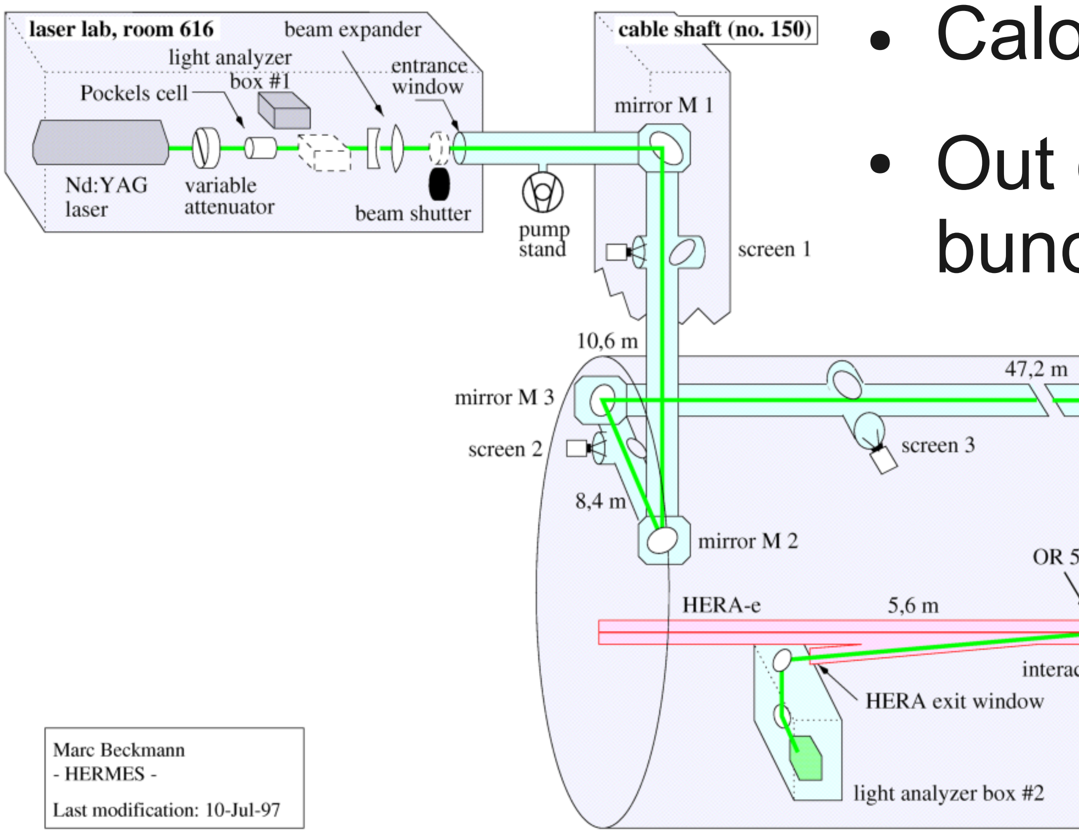

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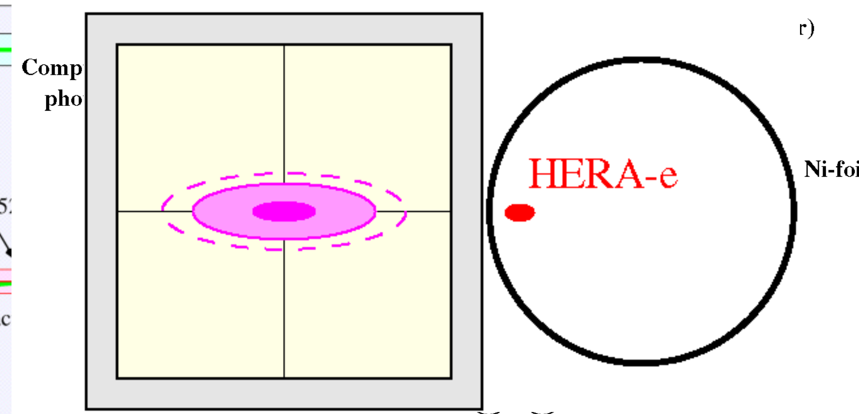
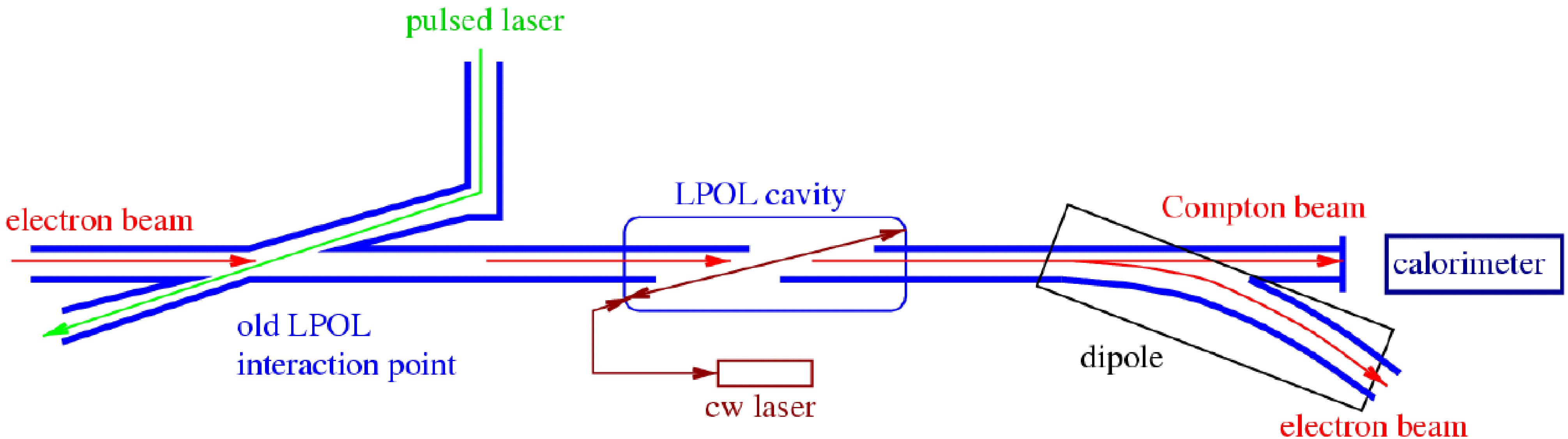


Longitudinal Polarimeter (LPOL)

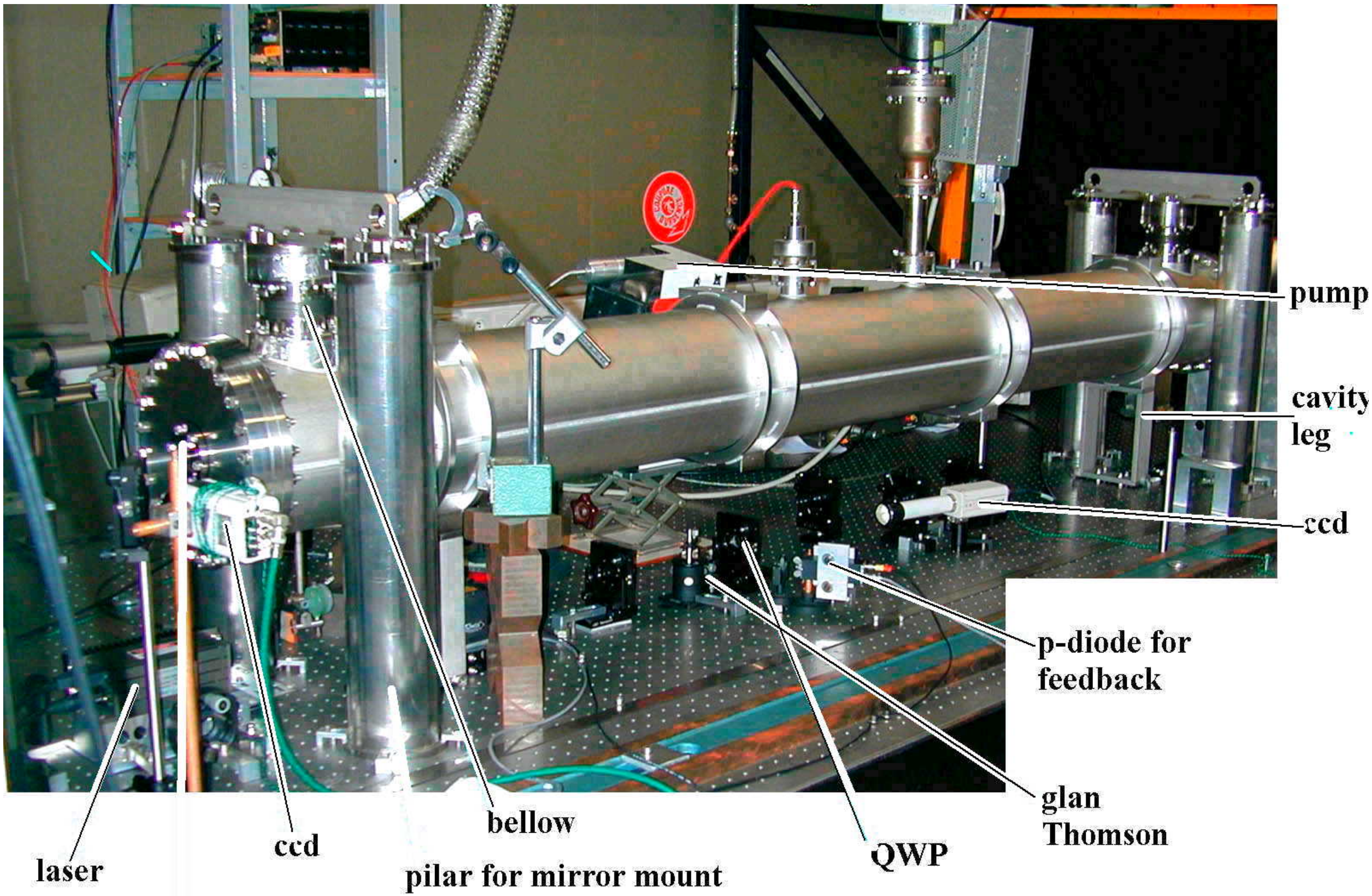
- Main systematic uncertainties of LPOL (total = 1.6%)
  - Analyzing power = energy-weighted integrated asymmetry (for integrating mode) needs to be extrapolated from single to multiple photons
  - Linearity of the calorimeter (constant gain monitoring, periodic current and laser power scans)
  - Electron beam position and slope changes
- In 2005–2007: larger differences between LPOL/TPOL
  - Not understood: each system seems working as expected
  - Indicates importance of having multiple measurements
  - Need **third measurement** method to pin-point problems

Cavity Polarimeter

- Intended as upgrade to ‘old’ LPOL for 2004–2007
- CW Fabry-Pérot cavity just downstream of LPOL interaction point (same straight line, same detector)
- Sampling calorimeter for single photon mode



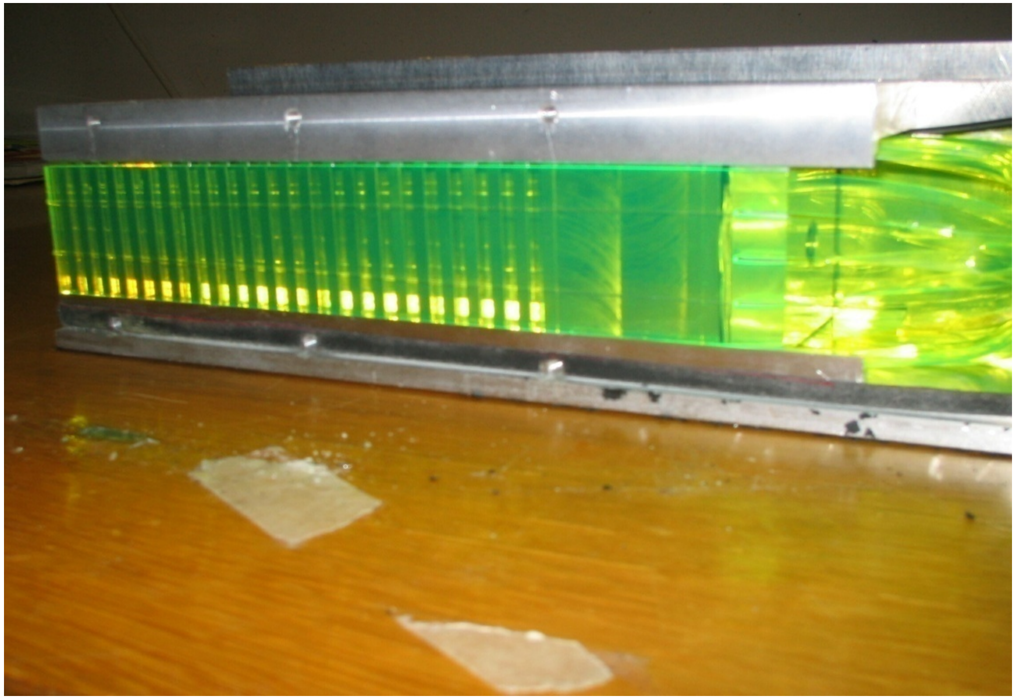
Cavity Polarimeter

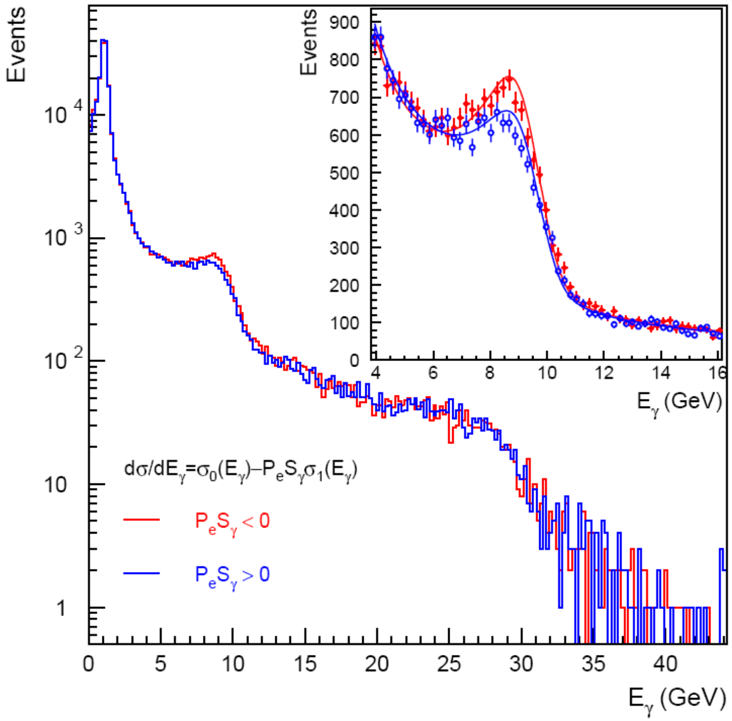


Cavity Polarimeter

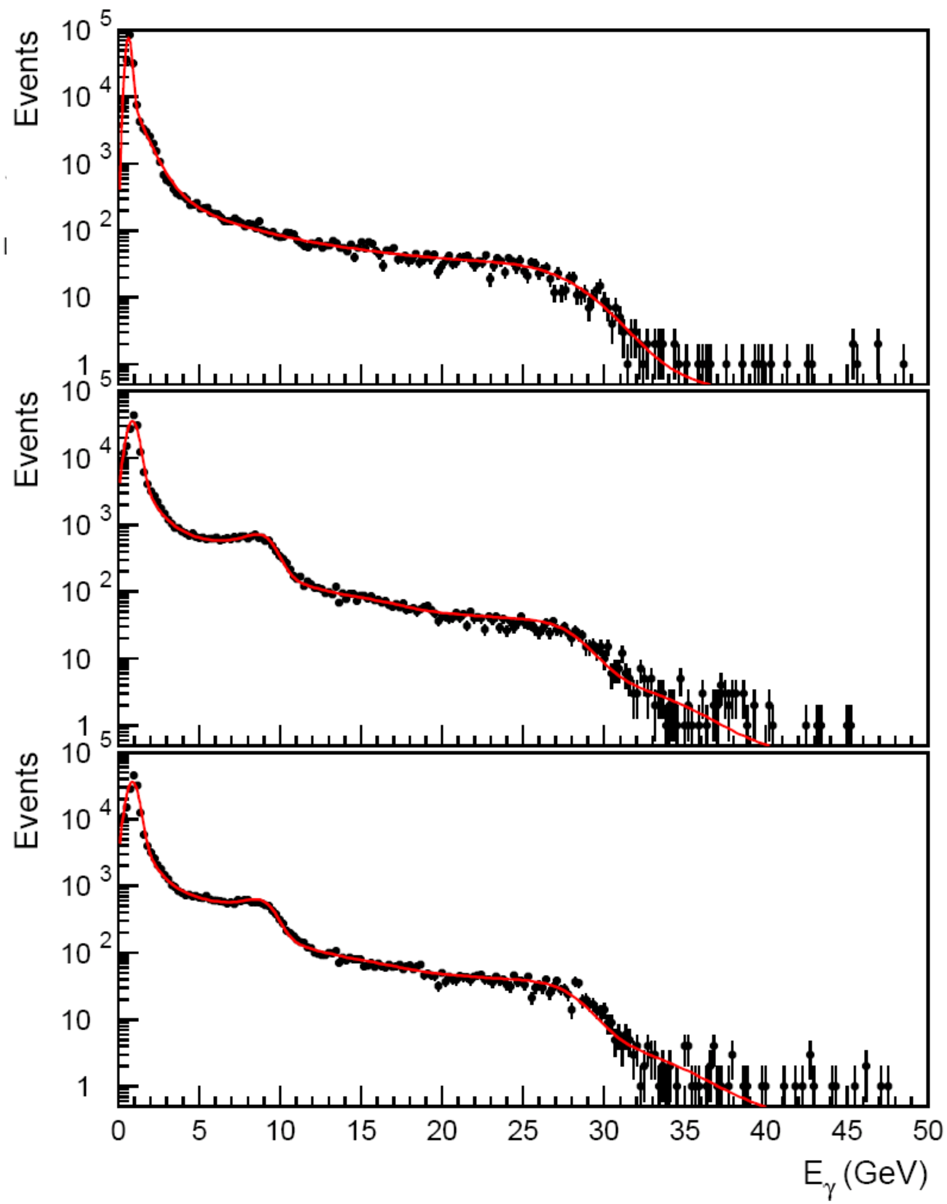
- Sampling calorimeter: tungsten/plastic tiles
- Single PMT read-out on wavelength shifters

- Tested in DESY and CERN test beams
- 1% linearity from 1 GeV up to 20 GeV





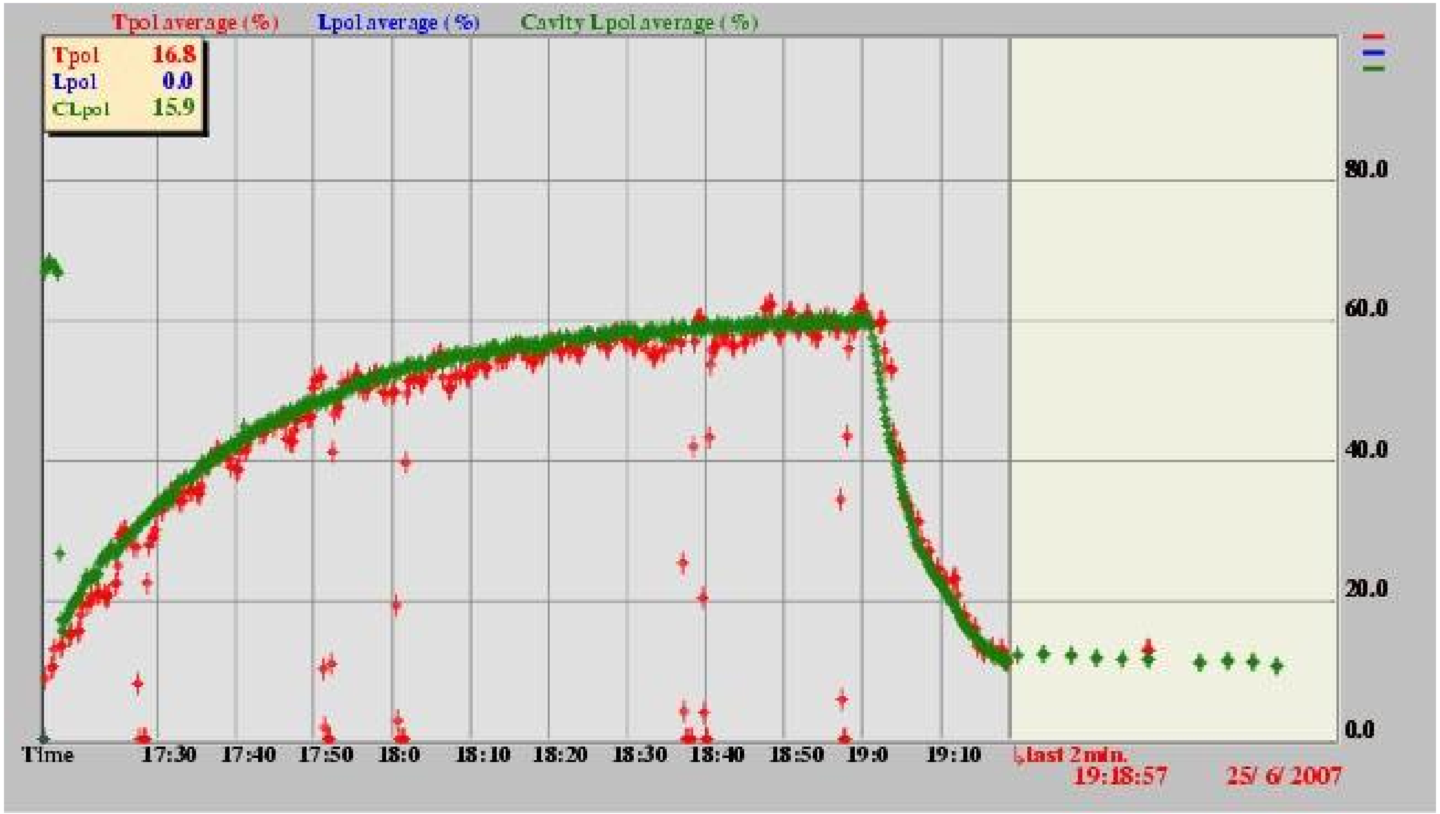
Cavity Polarimeter



- Measurement of the single photon energy
- One bunch (4 s + 4 s)
- Laser off: fit parameters
- Laser on (left and right): beam polarization and other beam-related parameters (4 s each)

Cavity Polarimeter

- Comparison TPOL and Cavity
  - Sokolov-Ternov rise-time measurement to set absolute scale
  - Unfortunately LPOL and Cavity operated only exclusively



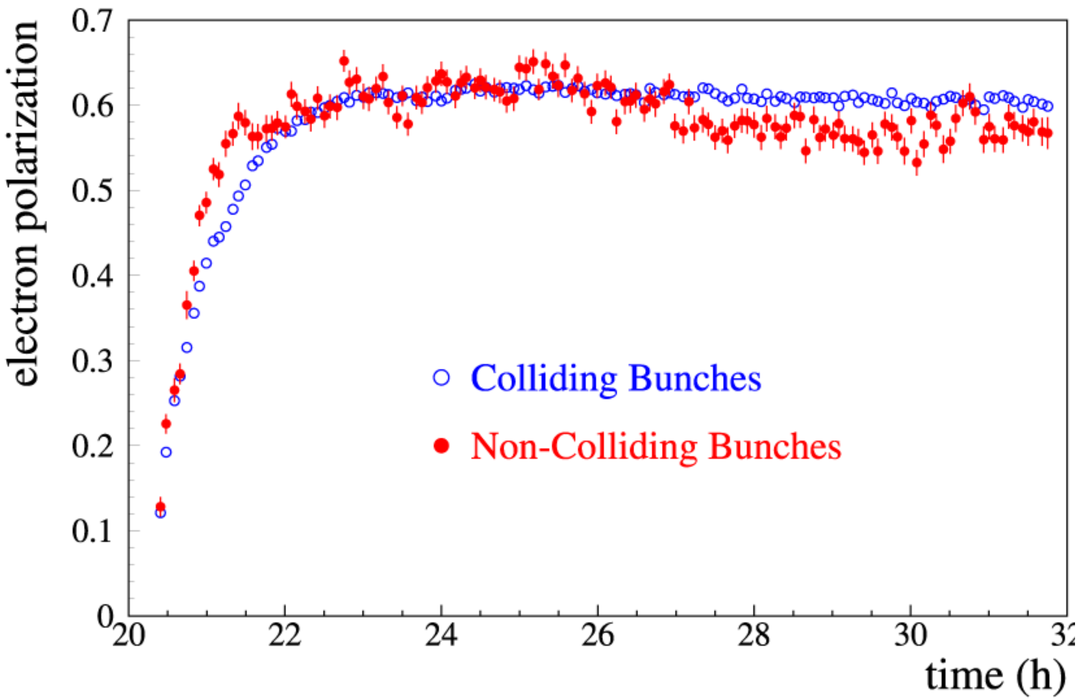
- 5 times more cavity data points
- ...and smaller uncertainty!
- Unfortunately only very little actual running (laser stability)

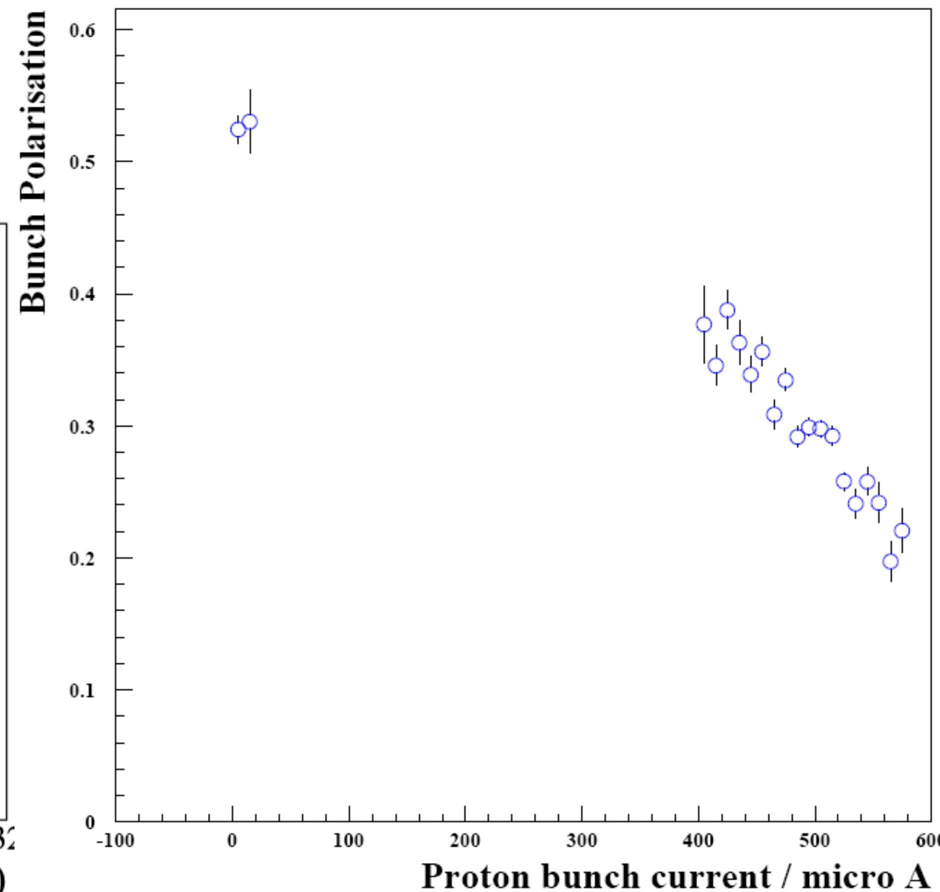
Compton Polarimetry at HERA

- Lessons learned
  - Precision of 1% challenging, even at 27.5 GeV
  - Polarization diagnostics should be included in lattice design
  - Measure polarization close to IP, avoid systematics due to beam optics between polarimeter and IP
  - Continuous measurement protects against drifts
  - Flip polarization often (at HERA: every few months...)
  - Multiple devices with different systematics for comparisons
  - Absolute measurement can be slow if relative measurements are fast and precise.

Compton Polarimetry at HERA

- Bunch-to-bunch polarization differences
- Beam-beam depolarization
  - Non-colliding in different tune



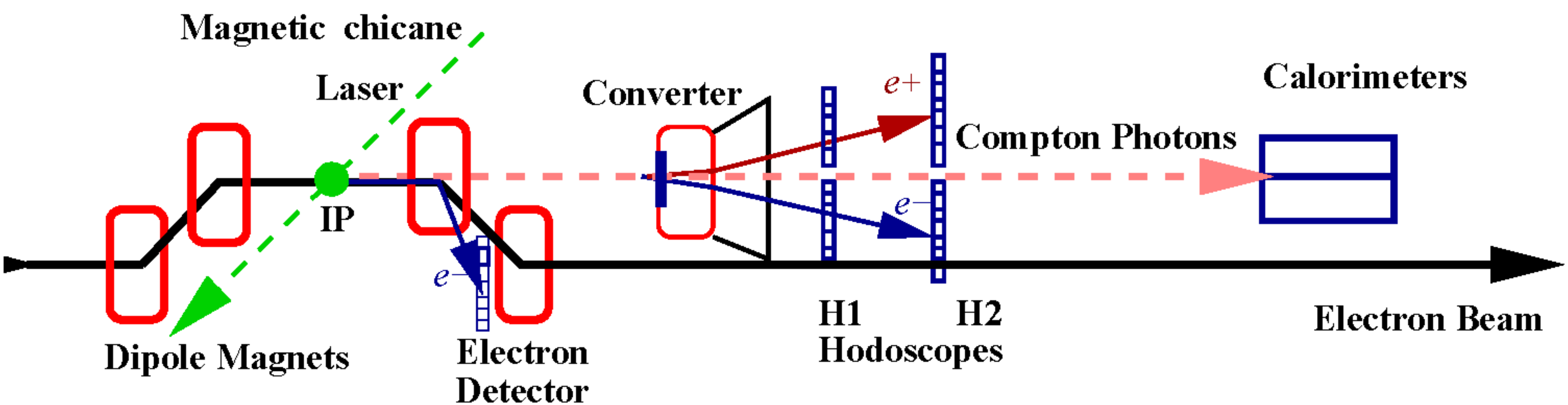


Electron Polarimetry at EIC

- Polarized electrons/positrons at the EIC
  - Energy of 3–20 GeV (between JLab and HERA)
  - Longitudinal polarization around 70% (transversely polarized beam injected, Sokolov-Ternov in the arcs, spin rotators)
  - Bunch separation 3–35 ns
- Polarimetry strategy
  - Use dedicated IP for polarimetry
  - Use multiple devices for redundancy and systematics
  - Compton polarimetry (unless atomic hydrogen jet Møller possibly proves feasible)

Electron Polarimetry at EIC

- Hybrid Compton Polarimeter
  - Chicane separates polarimeter from accelerator
  - Scattered electrons in strip detector (Si, diamond)
  - **Single** photons in pair spectrometer, variable converter
  - **Integrating** mode in sampling/crystal calorimeters



Hybrid Compton Polarimeter

- Chicane parameters
  - Length of 20 m, preliminarily inserted at s = 161 m IP
  - Electron deflection up to 22.4 cm (10 GeV), 6.7 cm (3 GeV) but could probably be reduced
- Sampling calorimeter
  - Geant4 simulations of plastic/tungsten and silicon/tungsten
  - Based on HERA calorimeters
- Pair spectrometer
  - Simulations in Geant4 for 10 GeV and 2.33 eV photons (using older ELIC lattice, needs some updating)
  - Slowed down after main analyzers changed employment

Summary

- Electron beam polarimetry at EIC
  - Compton polarimetry can reach 1% precision at 3–20 GeV
  - Precisions higher than 0.25% seem very difficult to reach
- Experience from HERA
  - Redundancy: multiple devices with different systematics
  - Cavity Compton polarimeter with sampling polarimeter
  - Combination of single photon and integrating modes
- Testbed at JLab 12-GeV
  - Very high requirements by parity-violation program
  - Overlap with JLab 12-GeV will be natural testbed
  - Upgrades of existing polarimeters (See Dave Gaskell's talk)

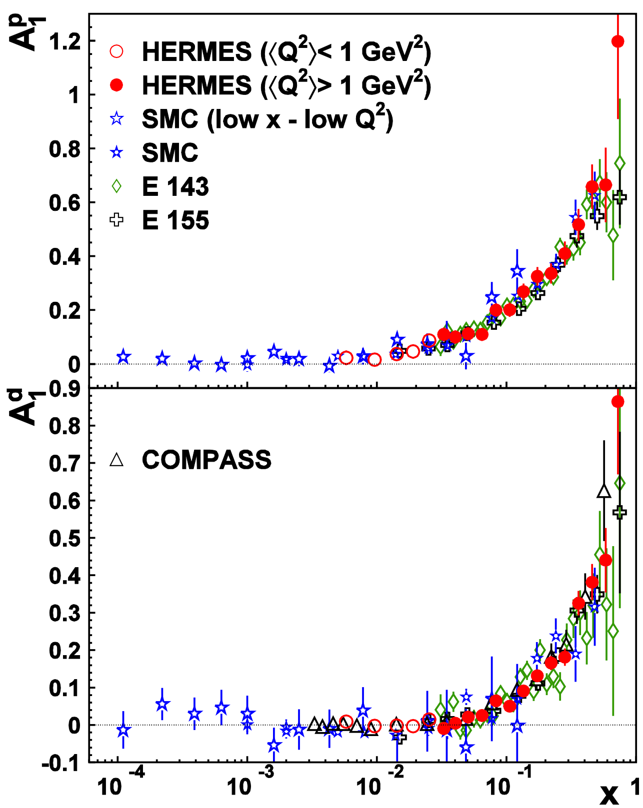
Summary

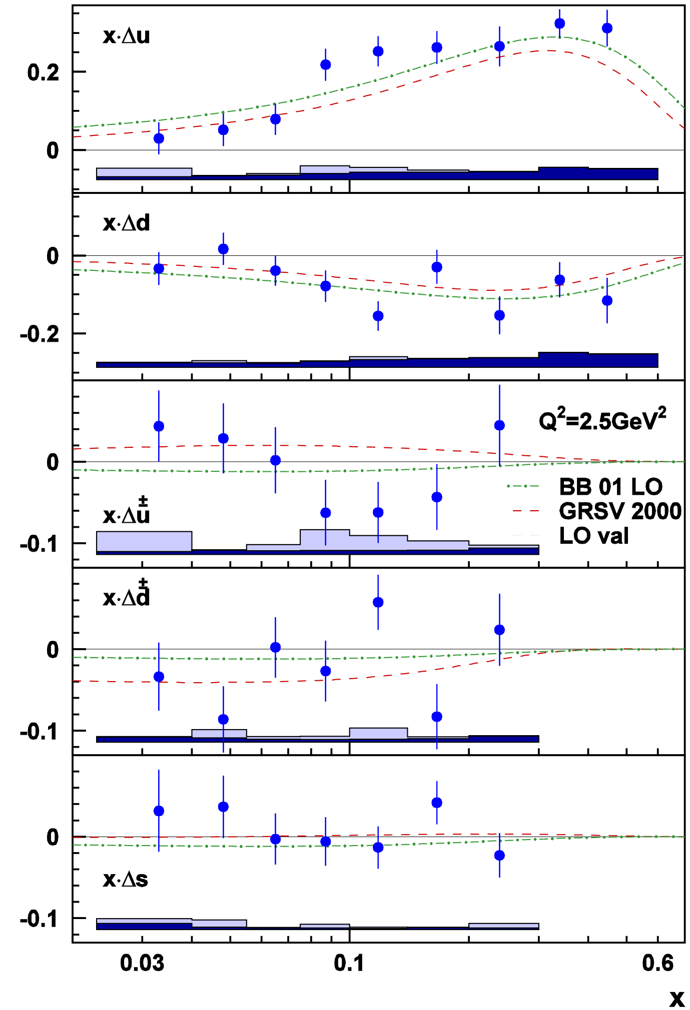
- Design ideas under consideration
  - Hybrid spectrometer design: simulations started
    - Conventional cavity laser system in chicane
    - Simultaneous single photon and integration mode
  - Atomic hydrogen jet Møller polarimeter (not covered)
  - Other processes: e-p elastic, A_1 asymmetries (not covered)
- EIC electron polarimetry group
  - Some reduction in manpower compared to the EIC electron polarization workshop in Ann Arbor ‘07 (Chudakov, Airapetian)
  - Interest in contributing from Paschke (UVa), Gaskell (JLab), BNL

Additional Slides

Electron Polarimetry at HERA

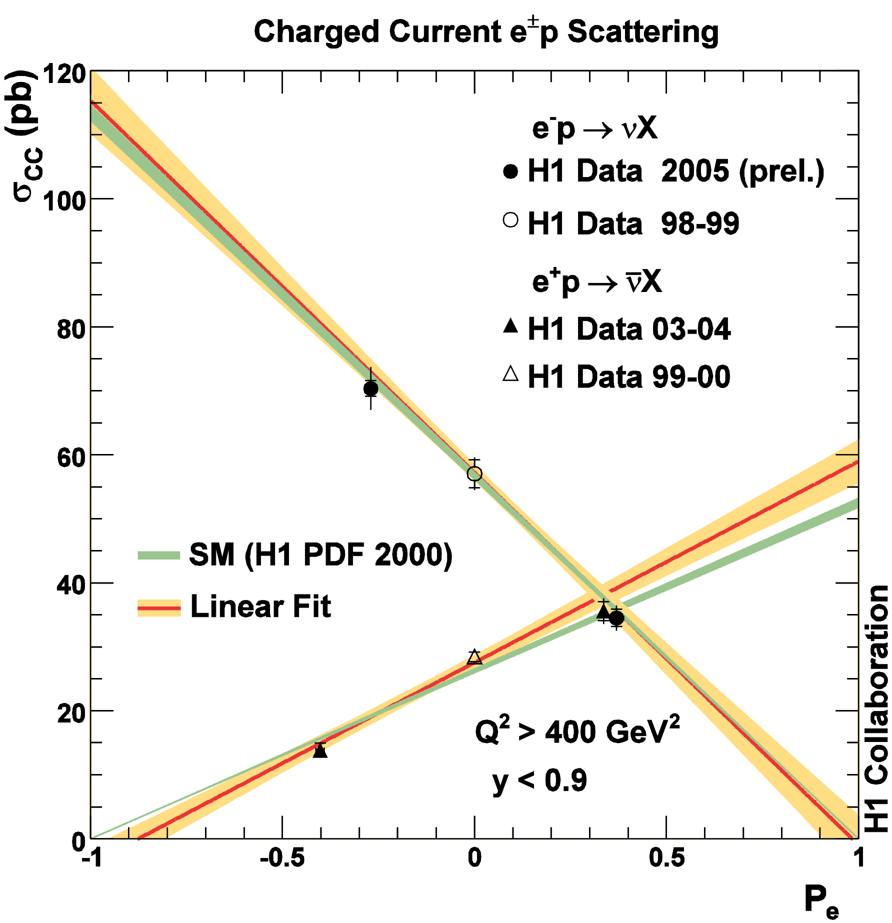
- HERMES: polarized electron beam, fixed target
  - Polarization of the sea quarks
  - Nucleon spin puzzle: ΔΣ

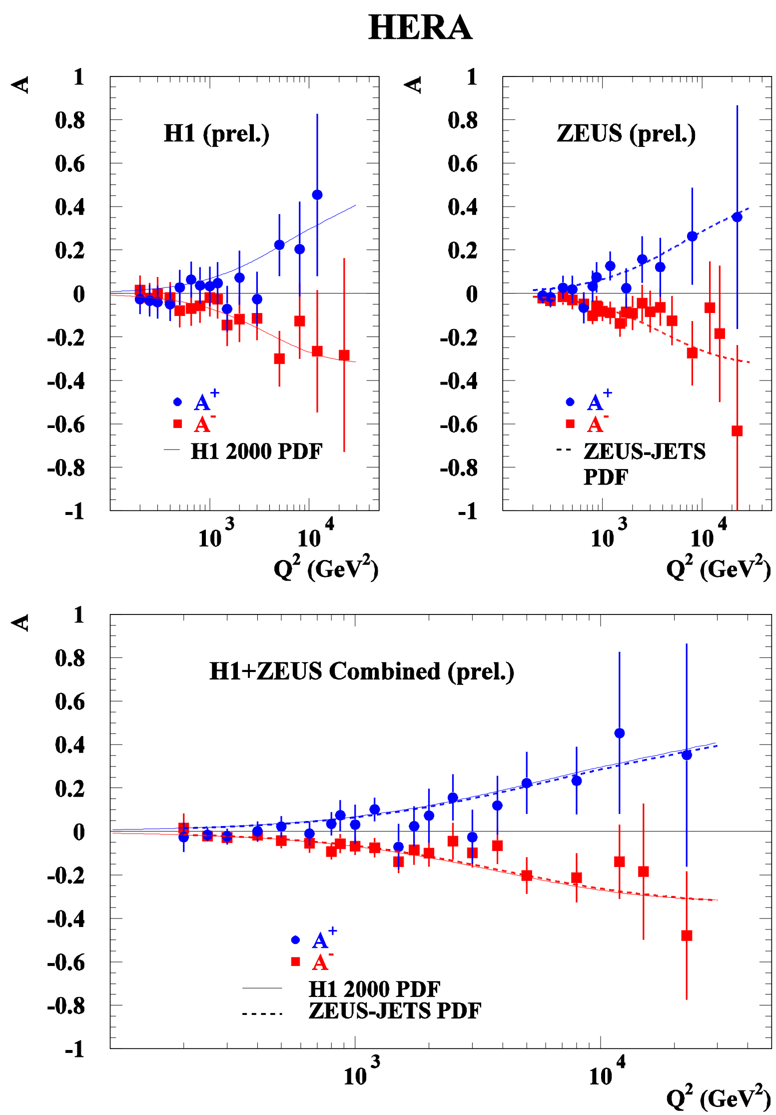




Electron Polarimetry at HERA

- H1 & Zeus: (polarized) electron-proton beams



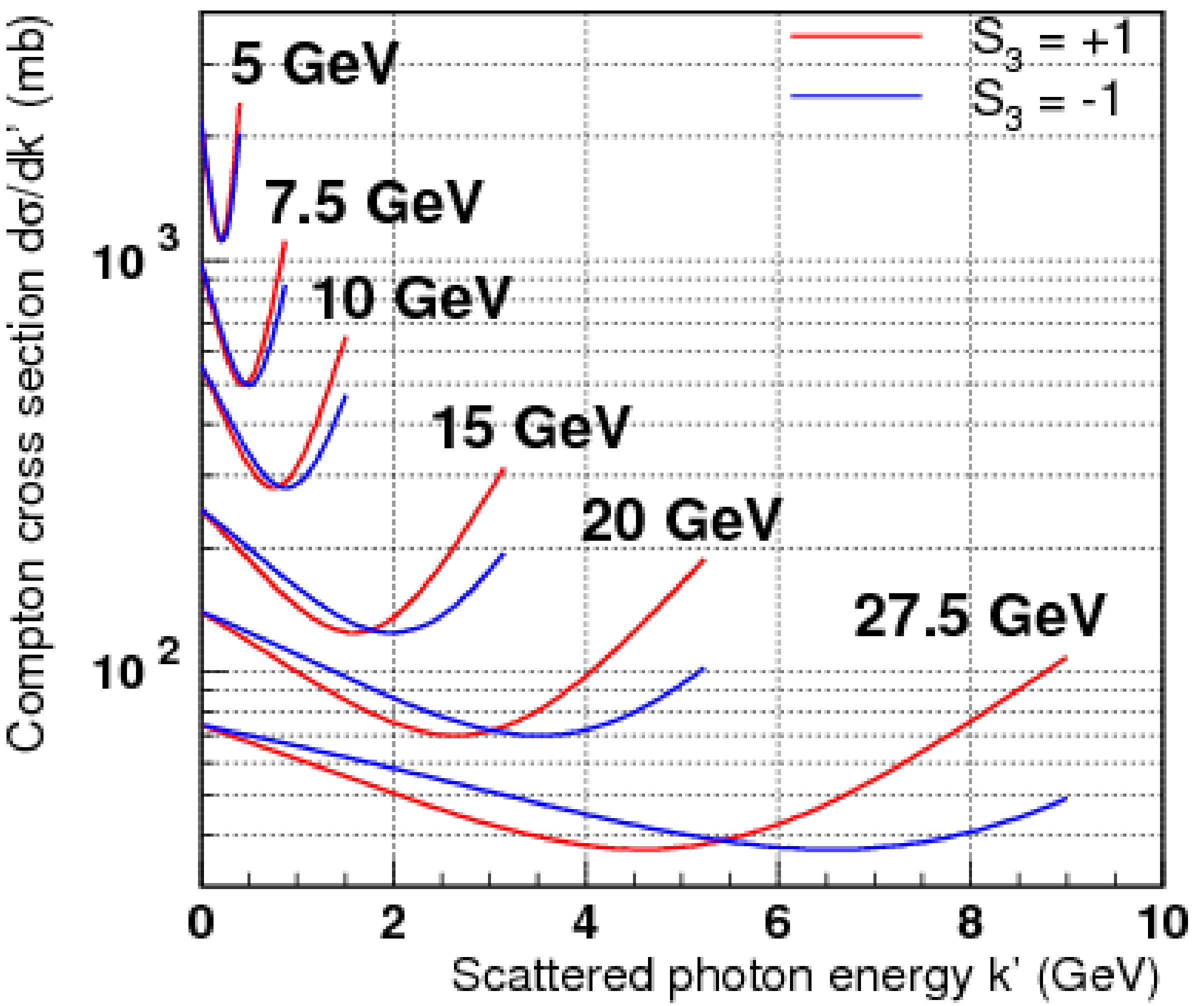


Electron Beam Polarimetry

- **Møller/Bhabha polarimeters**
  - JLab (A,B,C): < 12 GeV
  - Bates (linac): < 1 GeV
  - Mainz: < 1 GeV
- Because Møller polarimetry is invasive, Compton polarimetry seems to be preferable for the EIC (unless...)

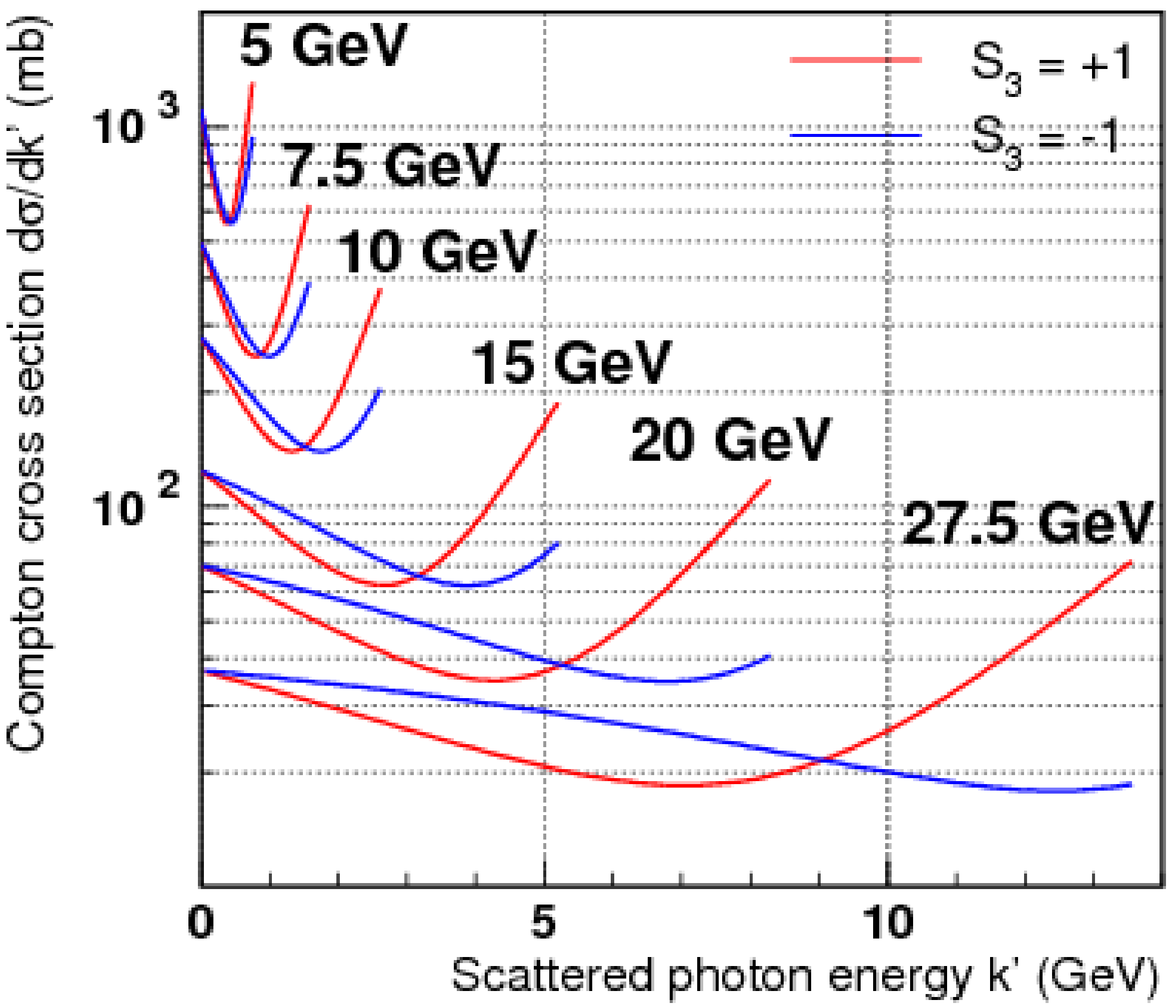
- **Compton polarimeters**
  - ILC: 45.6–500 GeV
  - EIC: 3–20 GeV
  - SLAC: 46 GeV (SLD)
  - DESY: 27.5 GeV
  - JLab: < 8–12 GeV (A, C)
  - Mainz: < 1.5 GeV (MAMI/PVA4)
  - Bates: < 1 GeV (South Hall)
  - Nikhef: < 1 GeV (AmPS)

Compton Polarimetry



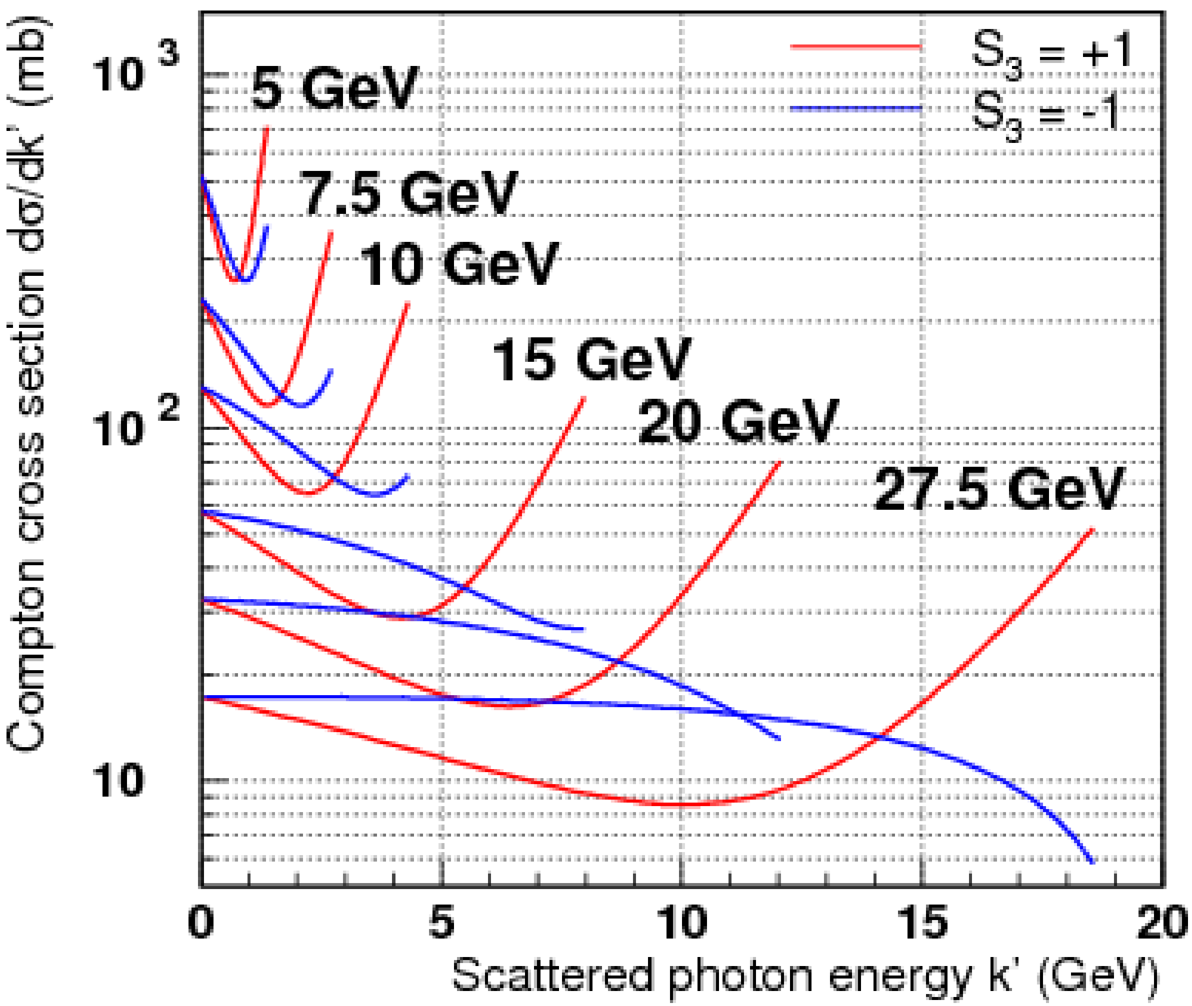
- Different cross section for laser helicity positive and negative
- Asymmetry larger at higher energy (HERA 27.5 GeV)
- Laser energy
  - 1064 nm (1.17 eV)

Compton Polarimetry



- Different cross section for laser helicity positive and negative
- Asymmetry larger at higher energy (HERA 27.5 GeV)
- Laser energy
  - 1064 nm (1.17 eV)
  - 532 nm (2.33 eV)

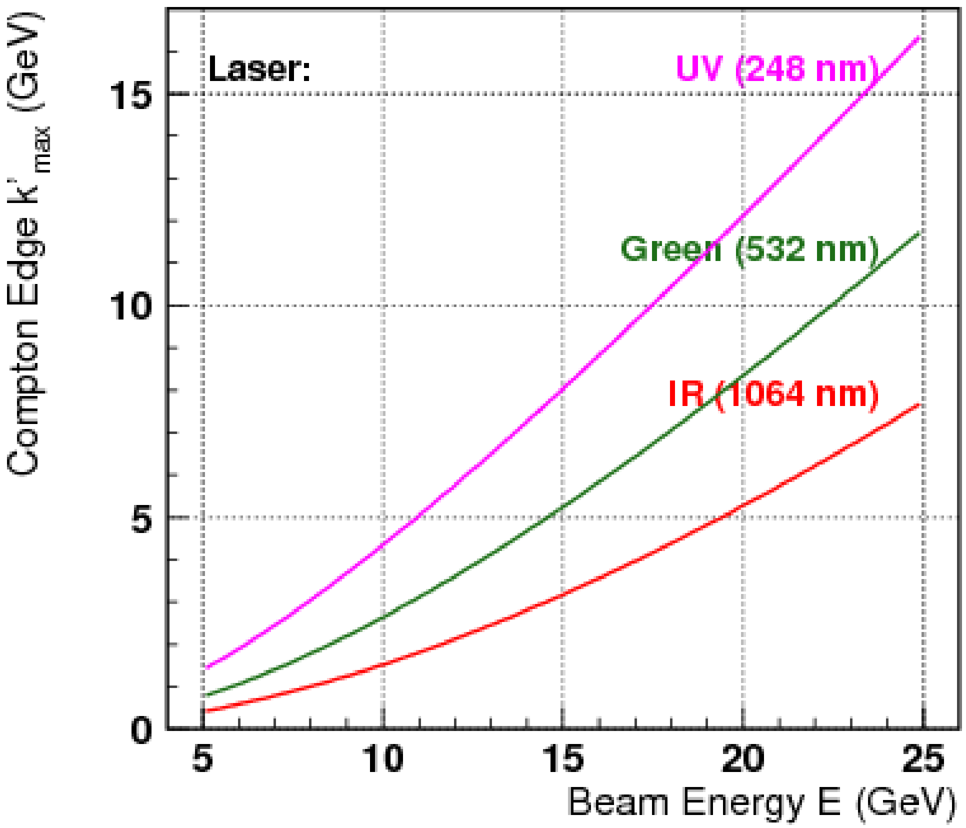
Compton Polarimetry



- Different cross section for laser helicity positive and negative
- Asymmetry larger at higher energy (HERA 27.5 GeV)
- Laser energy
  - 1064 nm (1.17 eV)
  - 532 nm (2.33 eV)
  - 248 nm (5.0 eV)

Compton Polarimetry

- Single photon mode: **measure energy of every Compton photon**
- Highest photon energy: Compton edge ~ $k \cdot E^2$



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- Single photon mode: **measure energy of every Compton photon**
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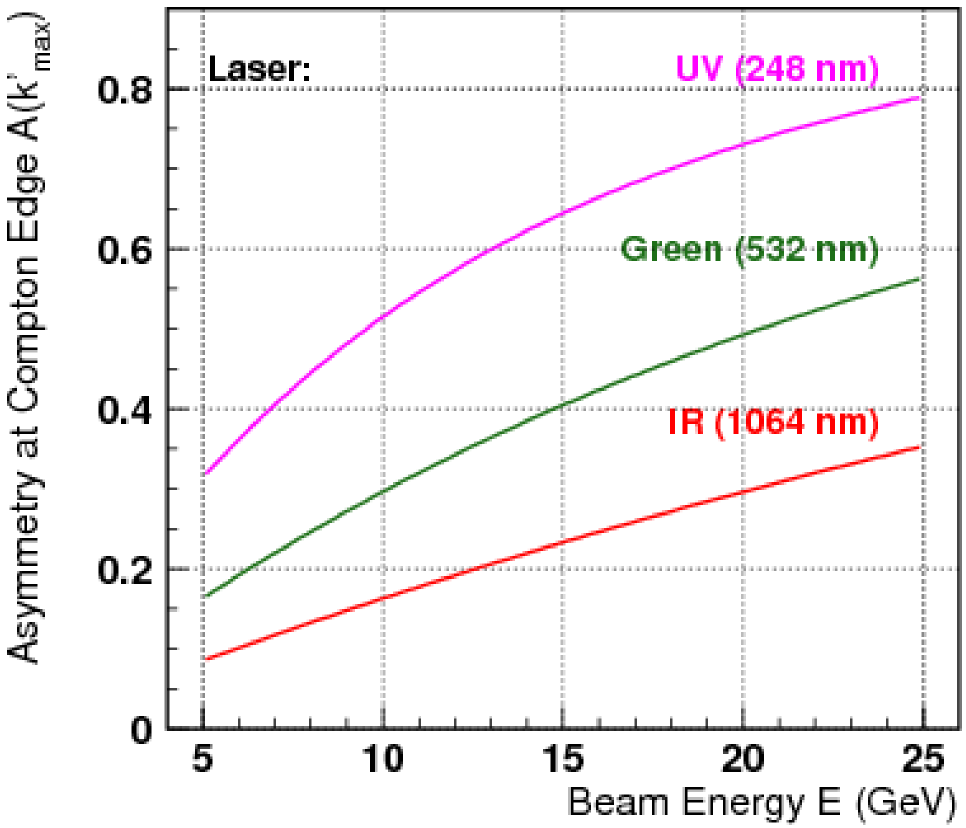
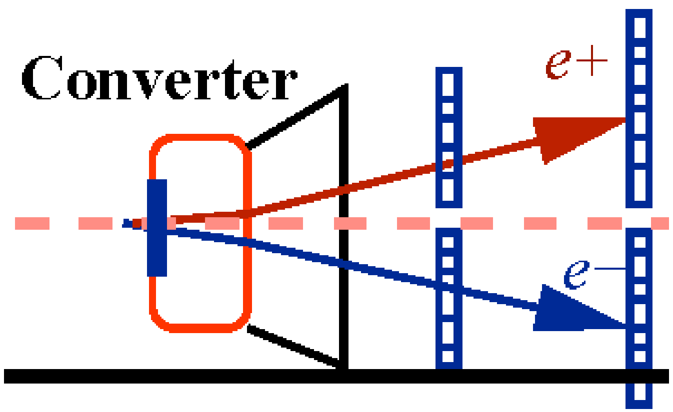
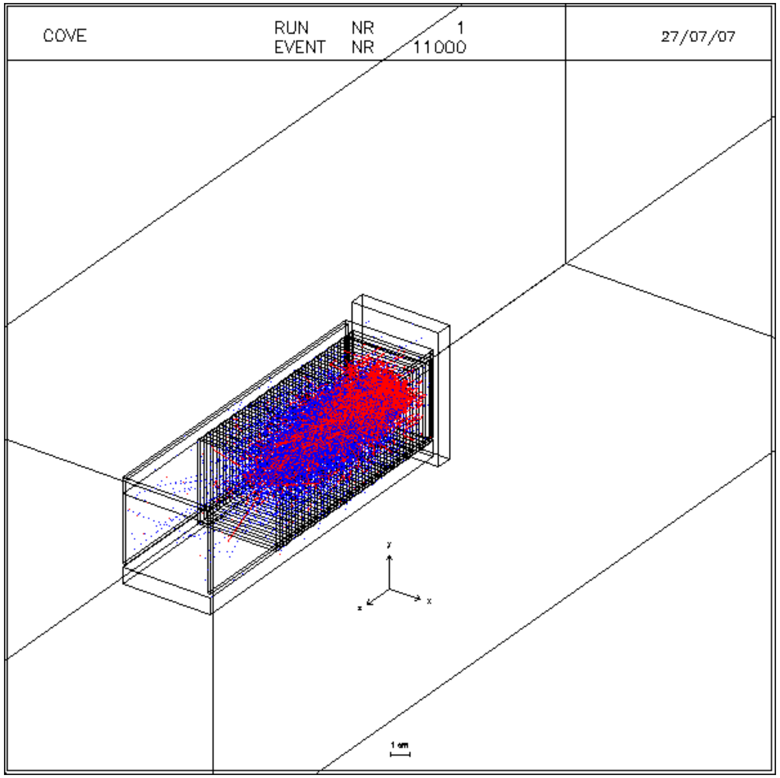
- Highest asymmetry (at Compton edge) ~ $k \cdot E$



Hybrid Compton Polarimeter

- Pair spectrometer
  - Mostly with pencil beams
  - Need to study smearing
- Sampling calorimeter
  - Geant3 → Geant4
  - Plans: fix configuration





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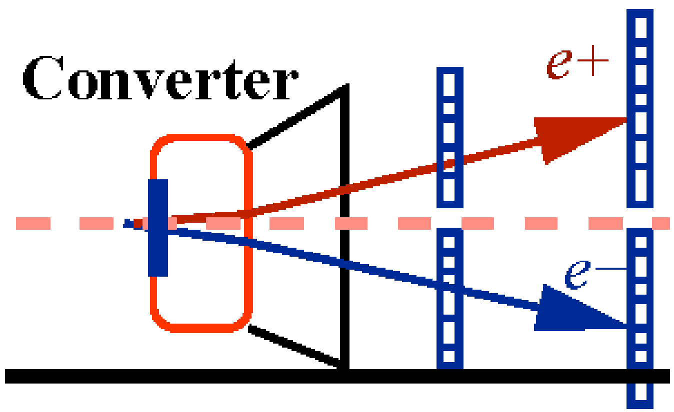

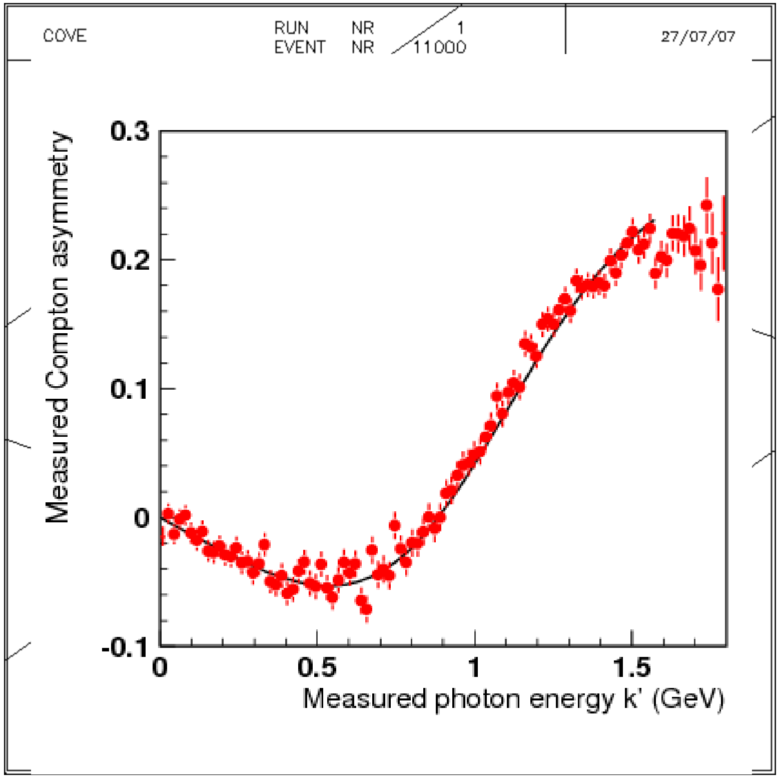

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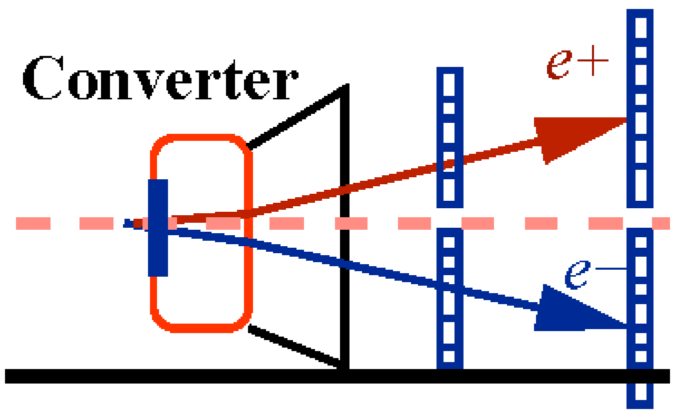

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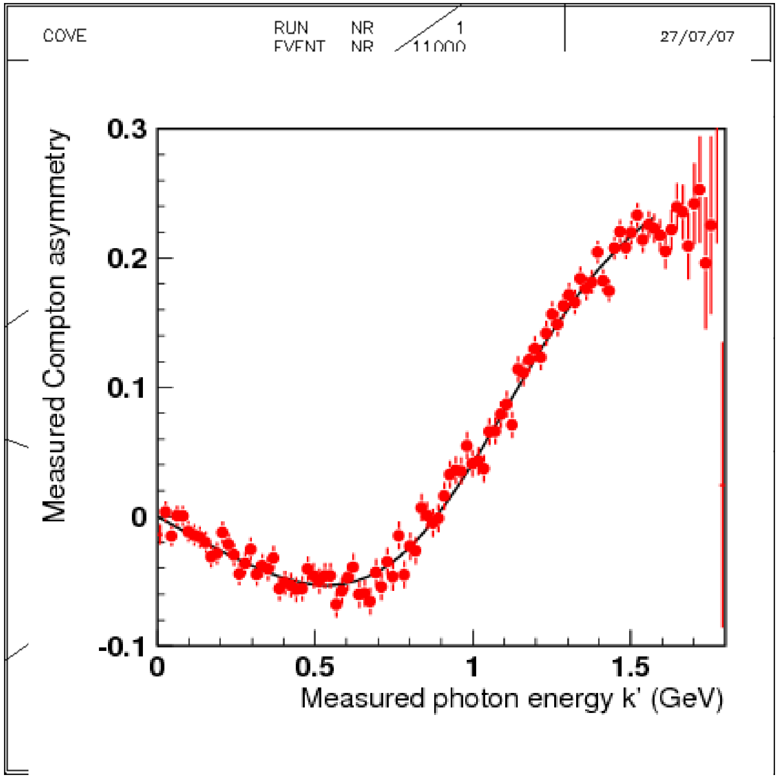

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