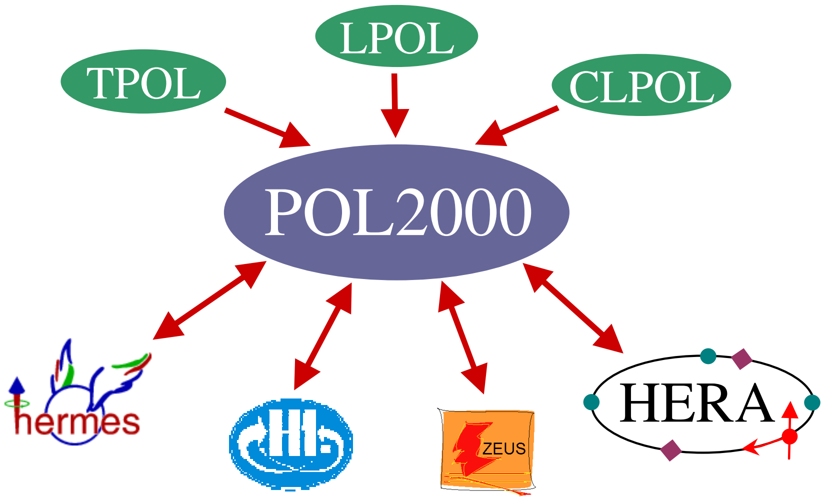
Polarization and Polarimetry at HERA

Blanka Sobloher
for the POL2000 collaboration



PST2009
September 7th 2009
Ferrara, Italy

Overview - Polarization and Polarimetry at HERA

- HERA and lepton polarization
  - HERA – Electron (positron) proton collider
  - Physics case – Why longitudinal polarization?
  - Sokolov-Ternov effect – Build-up of transverse polarization
  - Spin rotators – Rotating transverse to longitudinal
  - Polarization at HERA – Example for polarization build-up
  - Compton scattering – Basis for all three polarimeters at HERA

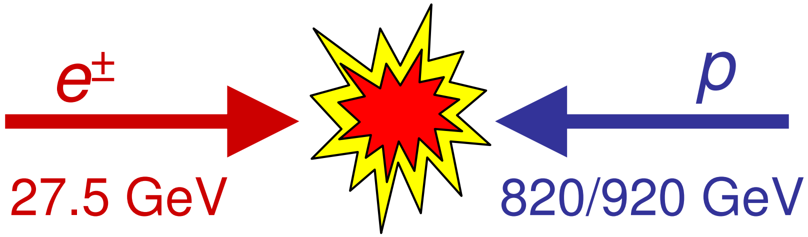
- Three polarimeters
  - Transverse polarimeter TPOL
    - Experimental setup, apparatus, polarization measurement and systematic uncertainties
  - Longitudinal polarimeter LPOL
    - Experimental setup, apparatus, polarization measurement and systematic uncertainties
  - Cavity longitudinal polarimeter
    - Experimental setup, apparatus, polarization measurement and systematic studies

- Conclusion and Outlook

HERA – Electron (Positron) Proton Collider

- $e^{\pm}p$ collider at DESY in Hamburg, Germany
- Operation 1992 – 2007
- Colliding experiments:

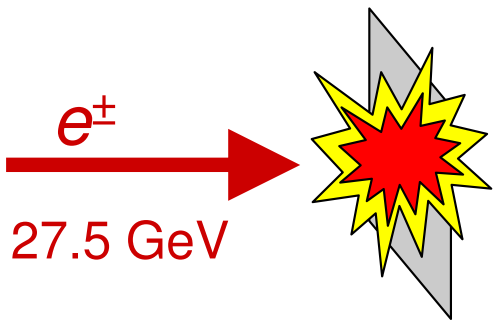
H1 and **ZEUS**



$\sqrt{s}$ = 300/318 GeV

- Fixed target experiments:

HERMES, **HERA-b** (with *p-beam*)



- *e*-beam polarized
- Longitudinal polarization delivered to
  - **HERMES** since 1995 (HERA I)
  - **H1** and **ZEUS** since 2001 (HERA II)

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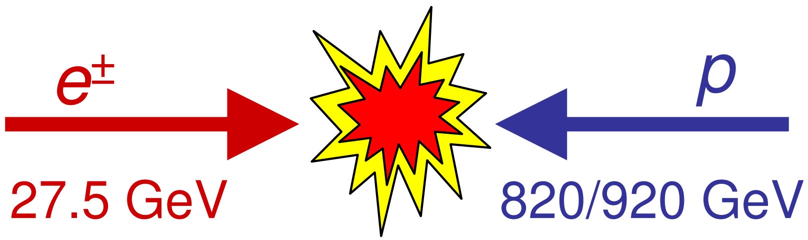

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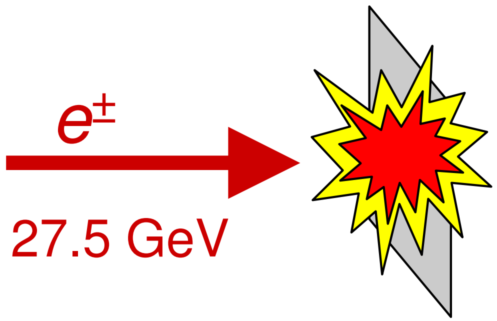
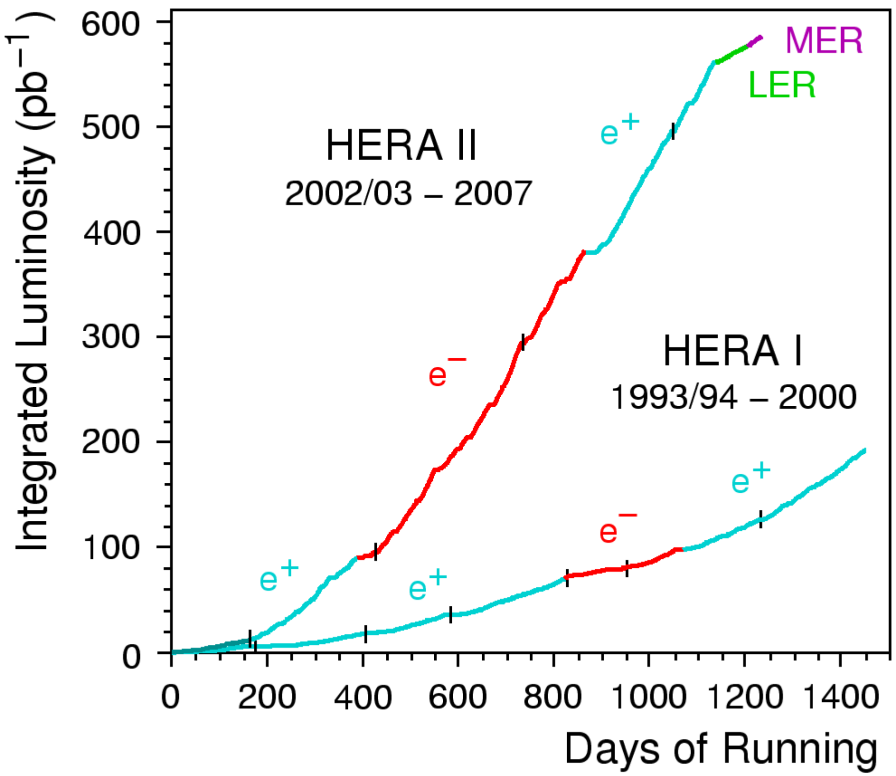




- *e*-beam polarized
- Longitudinal polarization delivered to
  - **HERMES** since 1995 (HERA I)
  - **H1** and **ZEUS** since 2001 (HERA II)
- Integrated luminosity: ~0.5 fb^{-1} collected per colliding experiment

Physics Case - Why longitudinal Polarization?

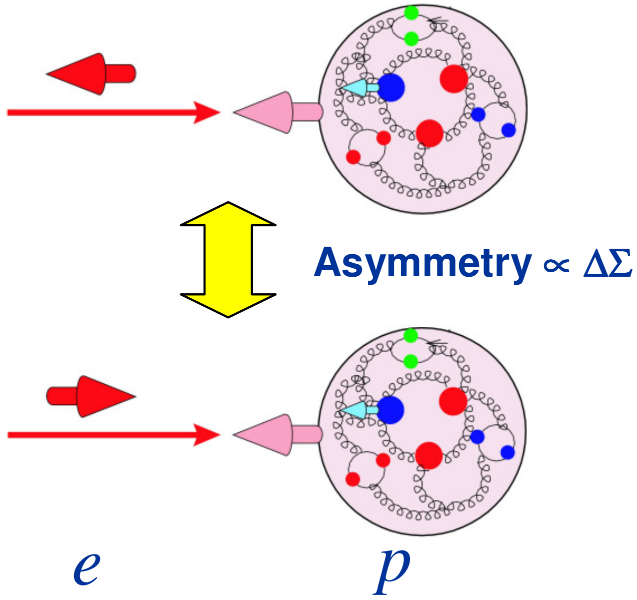
HERMES: Nucleon spin structure

- Determine the spin-dependent structure functions of nucleons

  → Spin-½ structure of the proton arises from its constituents:

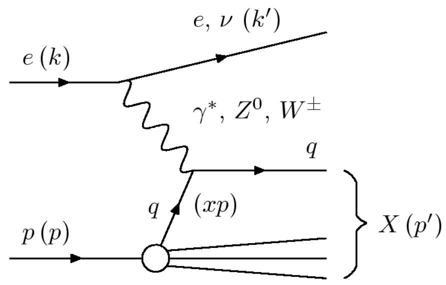
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$



Physics Case - Why longitudinal Polarization?

HERMES: Nucleon spin structure



- Determine the spin-dependent structure functions of nucleons

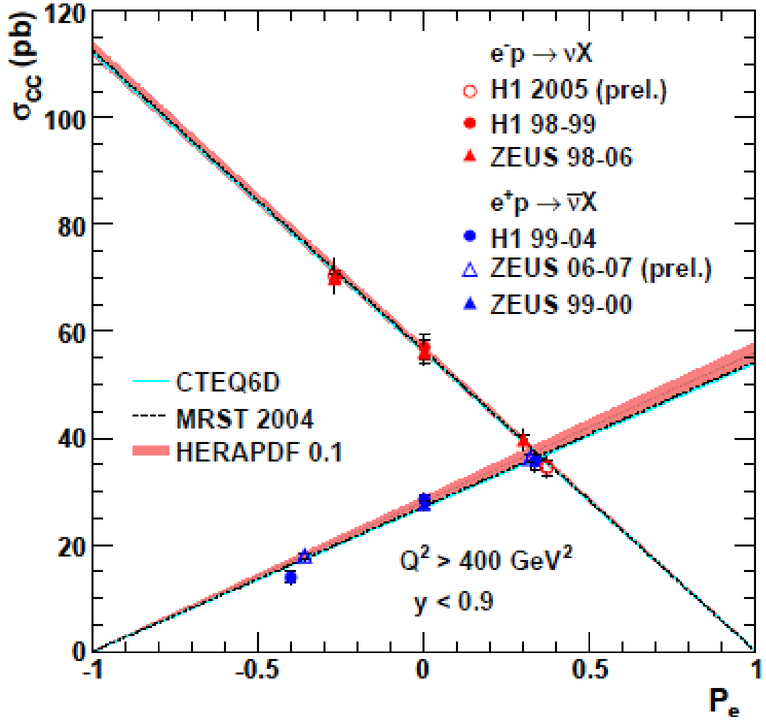
  ⟶ Spin-½ structure of the proton arises from its constituents

H1 and ZEUS:

- Chirality of charged current interactions
  - Polarization dependence of CC DIS cross section

    ⟶ Linear dependence according to Standard Model for leptons in both helicities
  - Search for right-handed *W* bosons (beyond the Standard Model)
    - Upper limit on non-vanishing cross sections at $P_e = \pm 1$

    ⟶ Set lower limit on W_R mass



$$\sigma_{\rm CC} = (1 - P_e)\sigma_{\rm CC}^{\rm L} + (1 + P_e)\sigma_{\rm CC}^{\rm R}$$

CC interactions: [Ant06,Gla09]

Physics Case - Why longitudinal Polarization?

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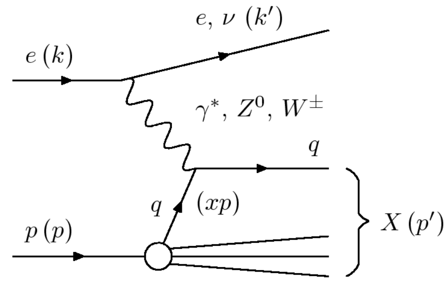


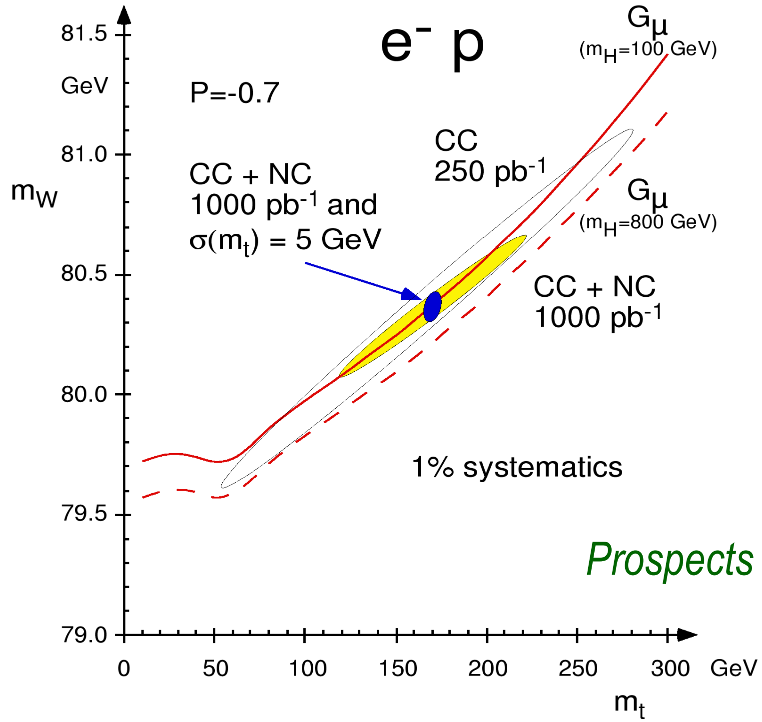
H1 and ZEUS:

- Chirality of charged current interactions
- Electroweak parameters: *W* boson mass
  - Ratio $\sigma_{\mathrm{NC}}/\sigma_{\mathrm{CC}}$ constrains *W* boson mass in (M_W, M_t) plane.

    ⟶ Standard Model consistent if M_W and M_t in agreement with other experiments

    ⟶ Test of electroweak universality
  - Sensitivity to electroweak mixing angle

$$\sin^2\theta_W = 1 - M_W^2/M_Z^2$$



EW@HERA: [BER+96]

Physics Case - Why longitudinal Polarization?

HERMES: Nucleon spin structure

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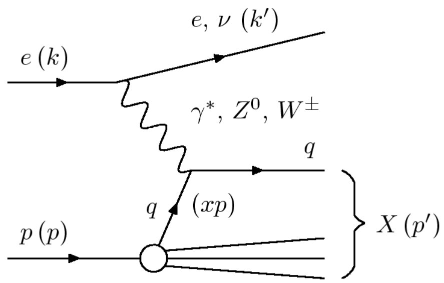
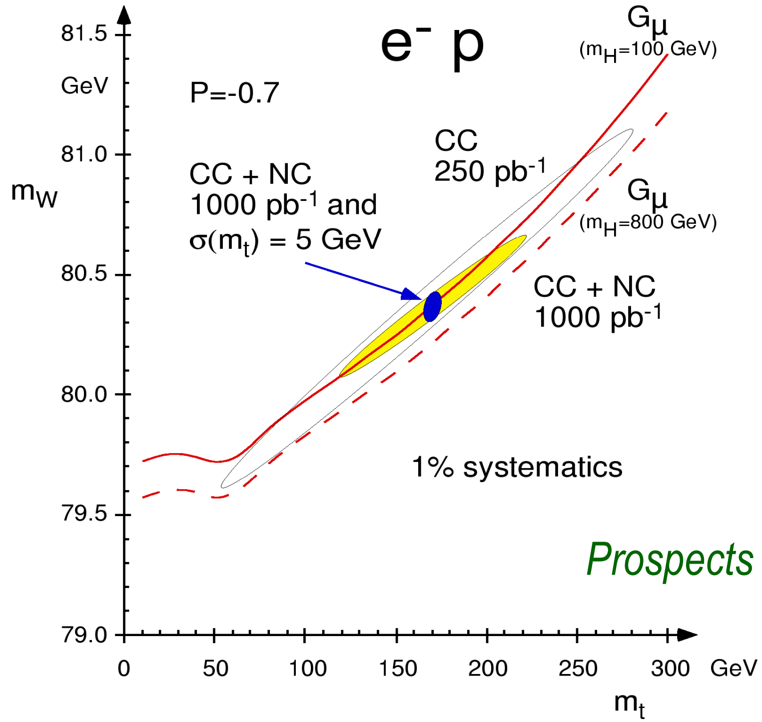


H1 and ZEUS:

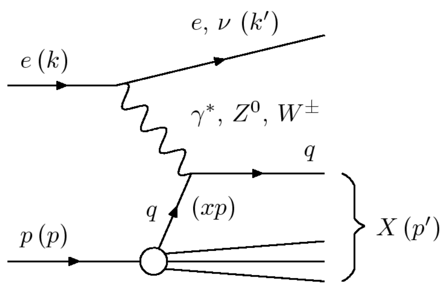
- Chirality of charged current interactions
- Electroweak parameters: *W* boson mass
- Light quark *(u,d)* neutral current couplings and γZ^0 interference structure functions F_2 and xF_3
  - Detailed comparison of polarized NC and CC cross sections

    → Measure all four *u*- and *d*-type vector and axial-vector couplings to the Z^0 boson



EW@HERA: [BER+96]

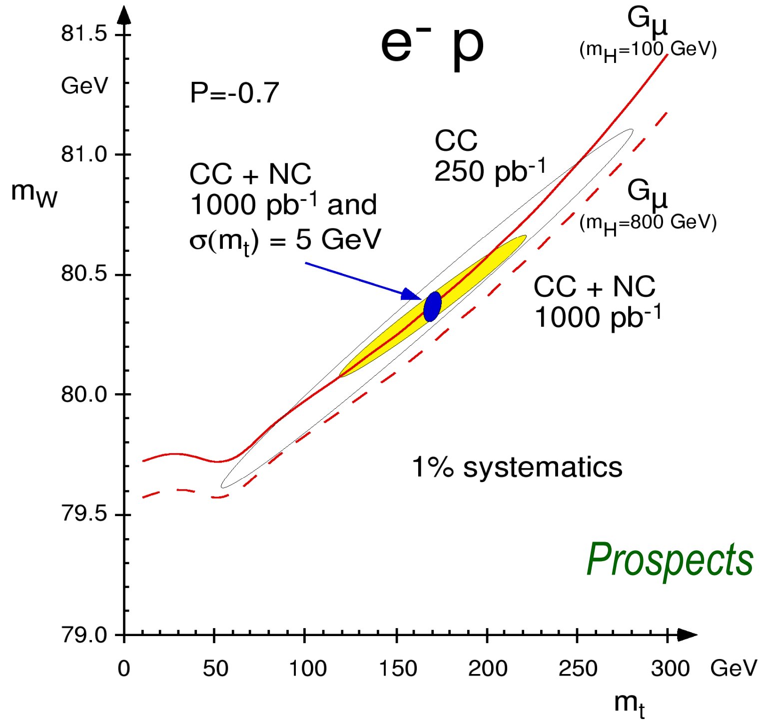
HERMES: Nucleon spin structure



- Determine the spin-dependent structure functions of nucleons

  $\longrightarrow$ Spin-½ structure of the proton arises from its constituents

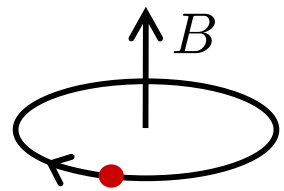
H1 and ZEUS:



- Chirality of charged current interactions
- Electroweak parameters: *W* boson mass
- Light quark *(u,d)* neutral current couplings and γZ^0 interference structure functions F_2 and xF_3
- Leptoquarks and Supersymmetry, …
  - NC DIS is main background to LQs, reduced by polarization
  - E.g. R-parity violating squark production, where only e_L^- and e_R^+ are involved

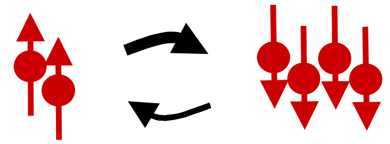
EW@HERA: [BER⁺96]

Sokolov-Ternov Effect - Build-Up of transverse Polarization



- Storage ring: particles move perpendicular to B-field of bending dipoles
- Particles emit synchrotron radiation upon bending

  $\longrightarrow$ Induces spin-flips



- Spin-flip transition probabilities differ: $\omega_{\uparrow\downarrow} \neq \omega_{\downarrow\uparrow}$

  $\longrightarrow$ Particle spins align (anti)parallel to B-field, defining polarization: $P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$

- Exponential build-up: $P(t) = P_{\rm st}\,(1 - e^{-t/\tau_{\rm st}})$
  - With asymptotic polarization limit and build-up time:

$$P_{\rm st} = \frac{\omega_{\uparrow\downarrow} - \omega_{\downarrow\uparrow}}{\omega_{\uparrow\downarrow} + \omega_{\downarrow\uparrow}} \approx 92.4\% \qquad \tau_{\rm st} = \frac{1}{\omega_{\uparrow\downarrow} + \omega_{\downarrow\uparrow}} \approx 100{\rm s} \cdot \frac{\rho^3}{E^5} \cdot \frac{\rm GeV^5}{\rm m^3}$$

- Depolarizing effects in real machine
  - Stochastic kicks by emission of synchrotron radiation
    - ➢ Induce oscillations of particles around the closed orbit
  - Misalignments and field errors in dipoles and quadrupoles
    - ➢ Induce spin diffusion weakening polarization build-up

  $\longrightarrow$ Smaller maximal polarization *P* and build-up time τ

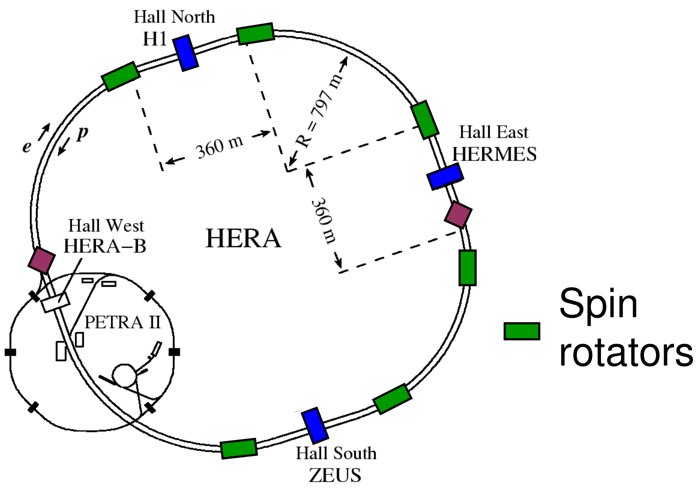
$$P_{\rm max} < P_{\rm st}$$

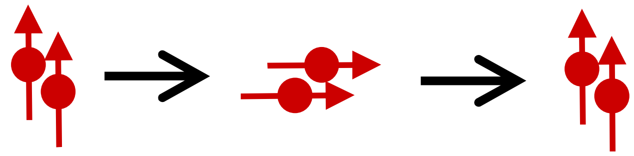
$$\tau_{\rm HERA} = \mathcal{O}(40{\rm min})$$

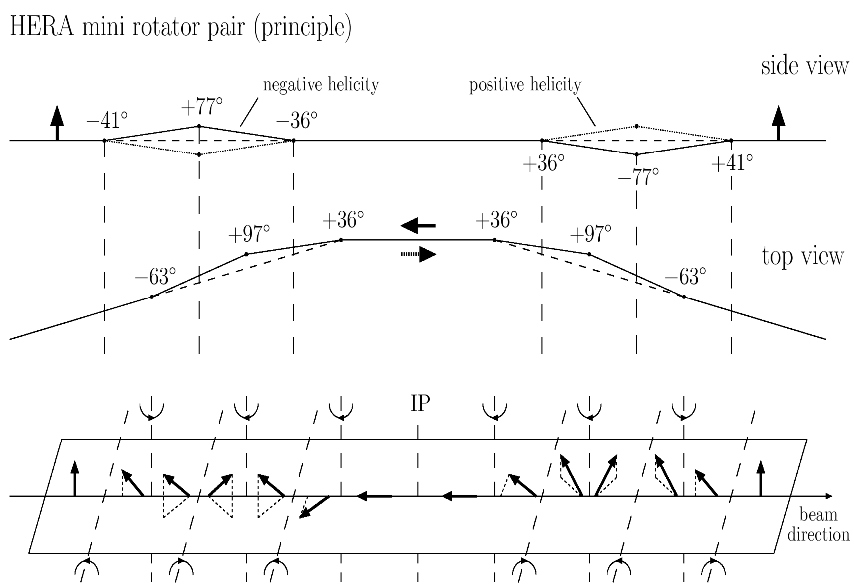
Sokolov-Ternov in storage rings: [ST64,B[+]94]

Spin Rotators - Rotating transverse to longitudinal

- Arcs of storage ring:
  - → Transverse polarization must be kept
- Straight sections with interaction points:
  - → Longitudinal polarization, if surrounded by a pair of spin rotators
- Rotate natural transverse polarization to longitudinal (and back)
  - By series of 6 alternating vertical and horizontal bends (dipoles)
  - Symmetric scheme
    - Takes part in bending of the arcs (effective horizontal bending)
  - Separation magnets inside experiments
    - Needed for head-on collision scheme
    - Have effect on spin-rotation too
    - ➢ Last rotator bend has to be weaker
- Both helicities possible
  - → Well-defined helicities: e_L and e_R



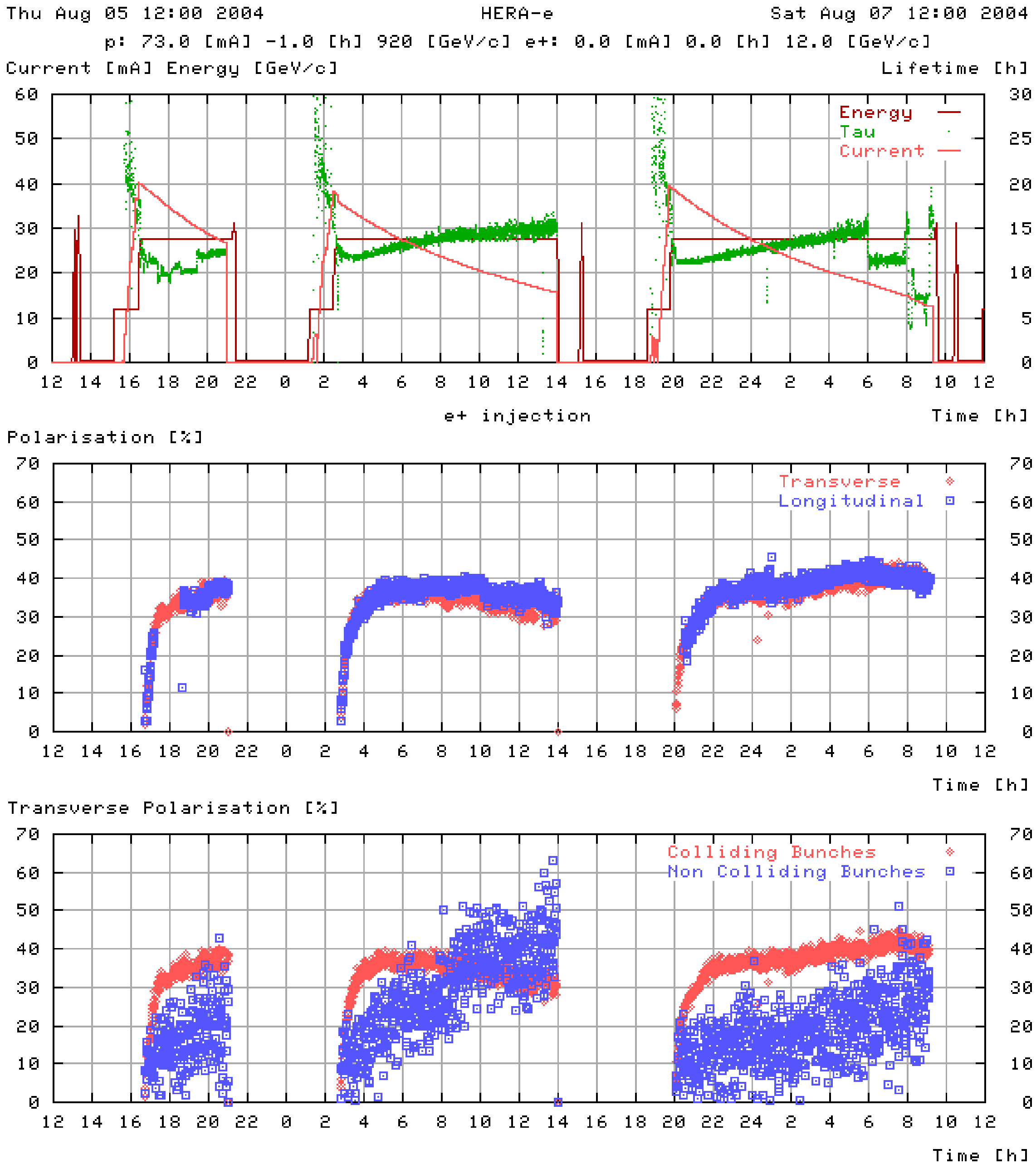




Mini rotators: [BS86]

Polarization at HERA - Example for Polarization Build-Up

- Typical values
  - $P_{max} \approx 40\%$
  - Rise times $\tau \approx 40$ min
- Continuous monitoring
  - Two fast, independent polarimeters
- Individual from fill to fill
  - Machine tuning to optimize orbits and other machine parameters
- Beam-beam interactions cause beam tune shifts
  - Colliding and non-colliding bunches have different polarization
  - Size of difference is subject to machine tuning
- Complete HERA II running period covered
  - → Over 99% of all physics fills had at least one polarimeter operational

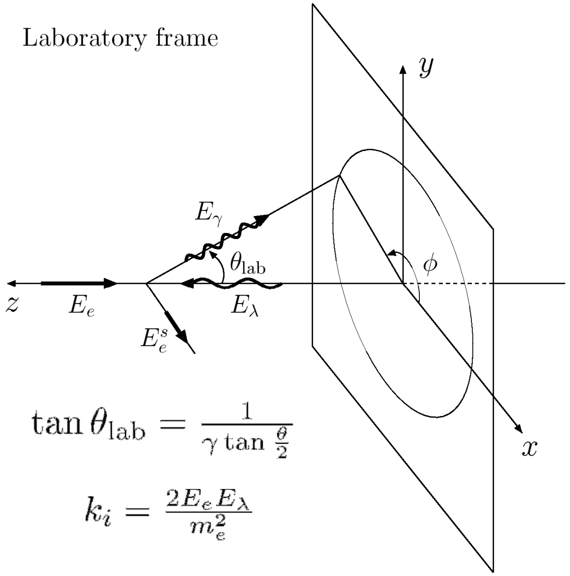


Build-up: [B+94]

Compton Scattering - Basis for all three Polarimeters at HERA

- Backscatter low-energy photons off high-energy electrons or positrons
- Correlation between scattering angle θ and photon energy E_γ

$$\cos\theta = \frac{E_e - E_\gamma(1+1/k_i)}{E_e - E_\gamma}$$



$$\tan\theta_{\rm lab} = \frac{1}{\gamma\tan\frac{\theta}{2}}$$

$$k_i = \frac{2E_e E_\lambda}{m_e^2}$$

- Kinematical endpoint

Compton edge $$E_\gamma^{\rm max} = \frac{2E_e}{2+1/k_i}$$

- Cross section dependent on polarization of both particles

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

- S_1, S_3 : linear and circular components of laser beam polarization
- P_Y, P_Z : transverse and longitudinal components of lepton beam polarization

$\longrightarrow$ Use asymmetry between S_3 = +1 and S_3 = -1 states for polarization measurement

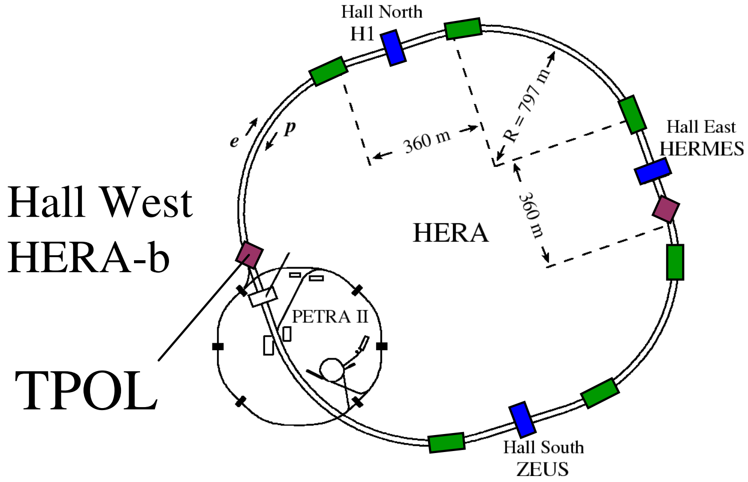
$$\mathcal{A}(y,E_\gamma) = \frac{\sigma_L(y,E_\gamma) - \sigma_R(y,E_\gamma)}{\sigma_L(y,E_\gamma) + \sigma_R(y,E_\gamma)}$$

Compton: [LT54a,LT54b]

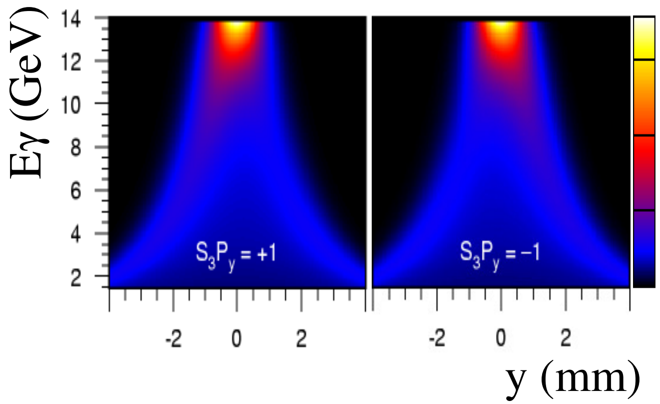
Transverse Polarimeter - Experimental Setup

- Measures transverse polarization in straight section West outside any spin rotators
- Operation 1993 - 2007
- Transverse polarization

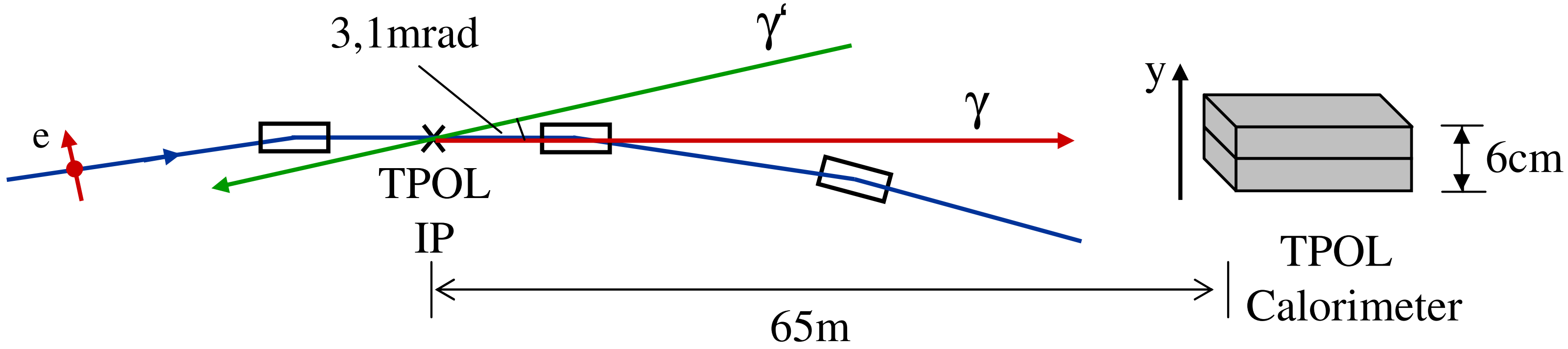
  → Spatial asymmetry between left and right laser helicity states



$$\mathcal{A}(y) = \Delta S_1 \frac{\int_{\Delta E_\gamma} \Sigma_1' \, dE_\gamma}{\int_{\Delta E_\gamma} \Sigma_0 \, dE_\gamma} + \Delta S_3 P_y \frac{\int_{\Delta E_\gamma} \Sigma_{2y} \, dE_\gamma}{\int_{\Delta E_\gamma} \Sigma_0 \, dE_\gamma}$$



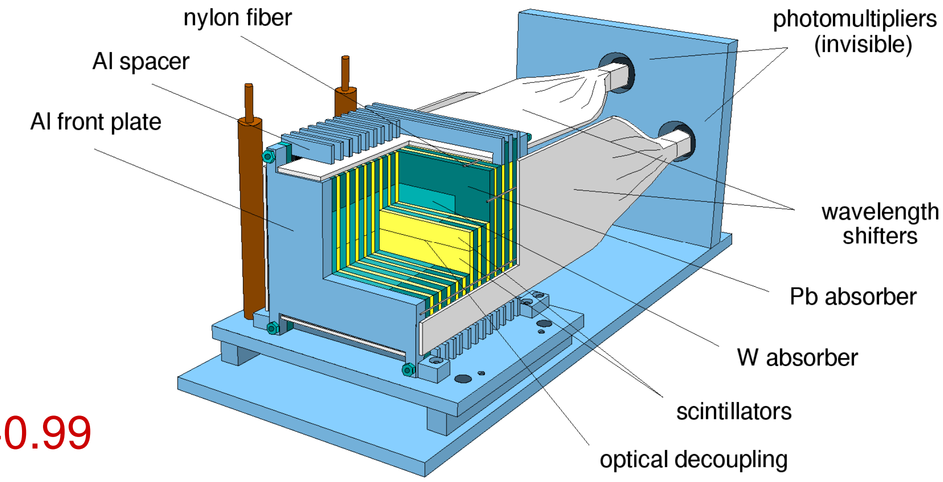
- Single-photon Mode: $n\gamma \approx 0.01$ per bunch crossing
  - Bremsstrahlung's background separately measured with laser off and subtracted statistically



Transverse Polarimeter - Apparatus

- Laser
  - Argon-Ion laser: green 514.5 nm (2.41 eV), 10 W cw
  - Circular polarization by Pockels cell, switched at ≈80 Hz
  - Light polarization monitored behind interaction point using Glan-prism

    ⟶ Measured circular polarization S_3>0.99



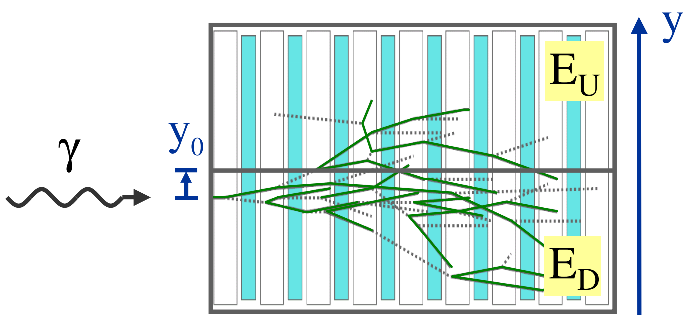
- Compact electromagnetic calorimeter
  - Scintillator-tungsten sampling calorimeter, ~$19X_0$ deep
  - Read-out with wavelength-shifters from all 4 sides: *Up, Down, Left, Right*
  - Upper and lower half optically isolated

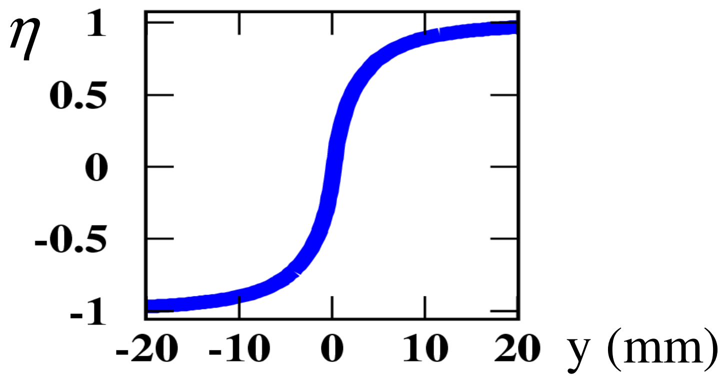
  ⟶ Impact position measurement by energy asymmetry

$$\eta = \frac{E_{\rm Up} - E_{\rm Down}}{E_{\rm Up} + E_{\rm Down}}$$

  ⟶ Photon energy measurement by energy sum

$$E_\gamma = E_{\rm Up} + E_{\rm Down}$$

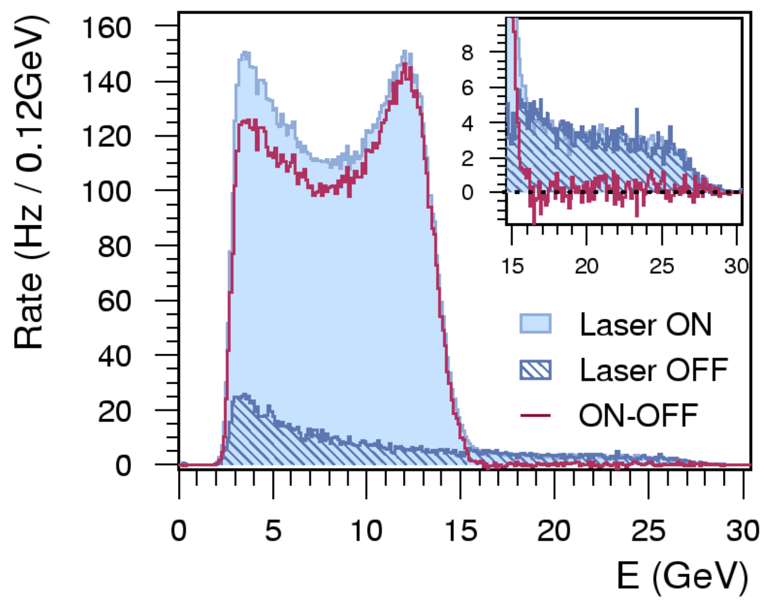




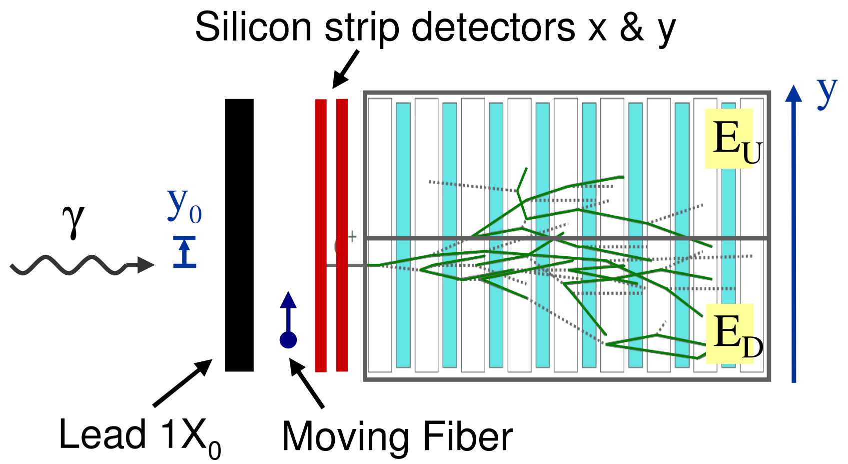
TPOL: [B+93,B+94]

Transverse Polarimeter - Apparatus

- Single-photon mode: photon rate ~100kHz
  - Absolute calibration using Compton edge
  - Main background bremsstrahlung
    - ➢ Statistical background subtraction using laser off data
  - Separate measurements of colliding and non-colliding bunches
  - Statistical uncertainty $\delta P/P \approx$ 2-3% per min
    - Single-bunches $\delta P/P \approx$ 10% per 10 min



- Upgrade 2000/2001
  - Fast DAQ enabling single-bunch measurement
  - Added position sensitive detectors and preradiator of $1X_0$ in front of detector (readout frequency ~2 kHz)
  - → In-situ measurement of ideal calorimeter response, i.e. ***η(y)*-transformation** and position dependent total response



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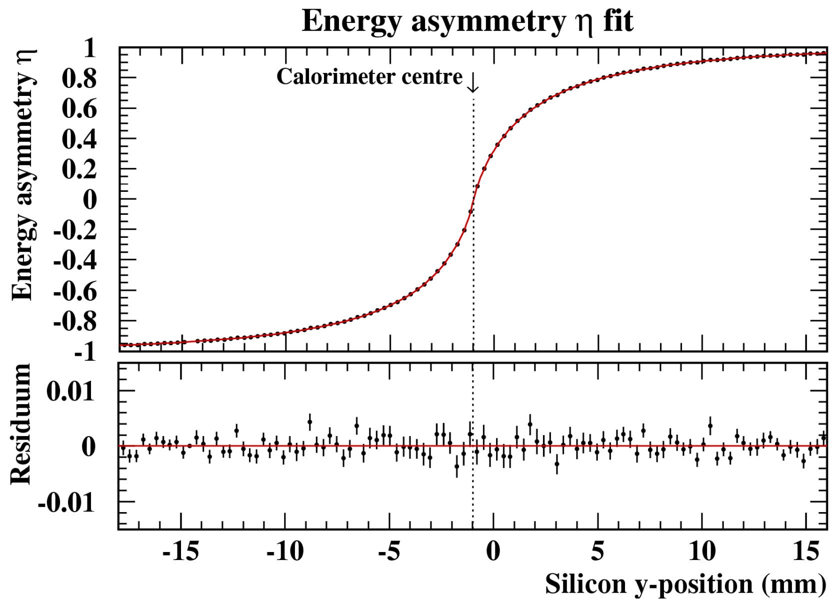
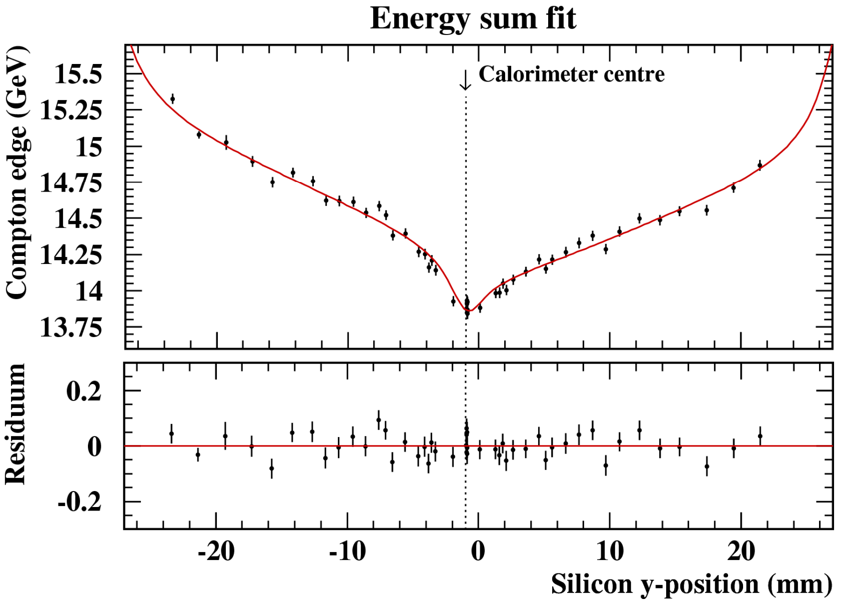
  - → In-situ measurement of ideal calorimeter response, i.e. ***$\eta(y)$*-transformation** and position dependent total response
  - Fit with analytical physical model using em shower description and detector effects





TPOL: [B+93,B+94]

Transverse Polarimeter - Polarization Measurement

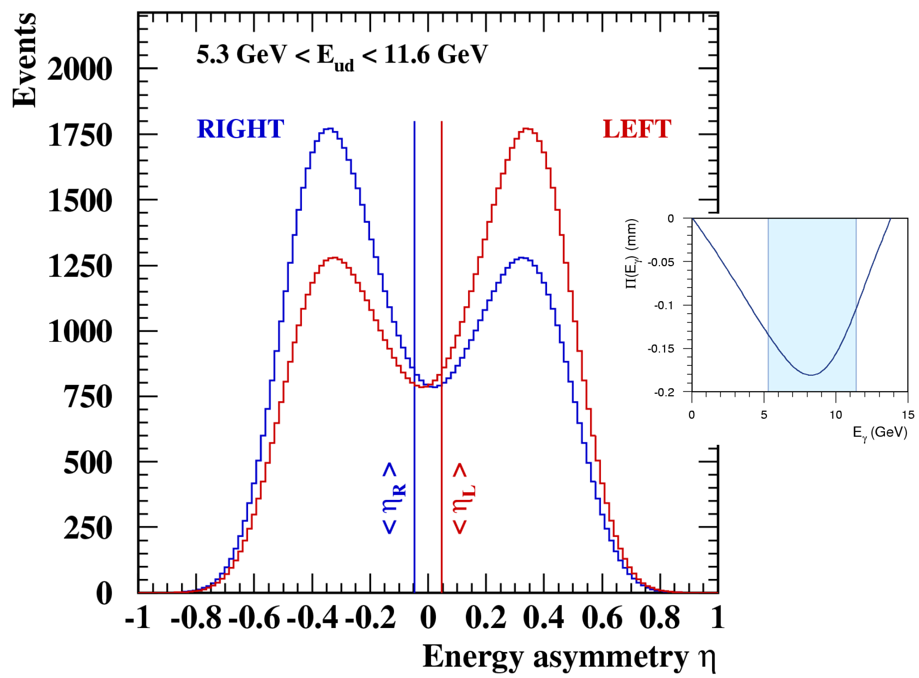
- Polarization measurement using spatial asymmetry of energy asymmetry η, switching laser between left and right
  - Polarization given by "shift of means"

$$\Delta\bar{\eta} := \bar{\eta}_{\mathrm{L}} - \bar{\eta}_{\mathrm{R}} := \Delta S_3 P_y \Pi_\eta$$

- HERA I analyzing power Π_η
  - Using Monte Carlo and rise time measurements in flat machine
- HERA II analyzing power Π_η
  - Beam conditions and detector changed
    - More variable beam size and divergence (focus) and Compton interaction distance to calorimeter
    - Exchanged calorimeter and added dead material in front

$\rightarrow$ Analyzing power became dependent on beam divergence and IP distance

$$\Pi_\eta \rightarrow \Pi_\eta(\sigma_{\mathrm{beam}}, D_{\mathrm{IP}})$$



- Determination of analyzing power dependencies for final polarization values still under study using Monte Carlo

$\rightarrow$ Planned: improvement of absolute scale and dependencies based on measured $\eta(y)$-transformation

TPOL: [B+93,B+94]

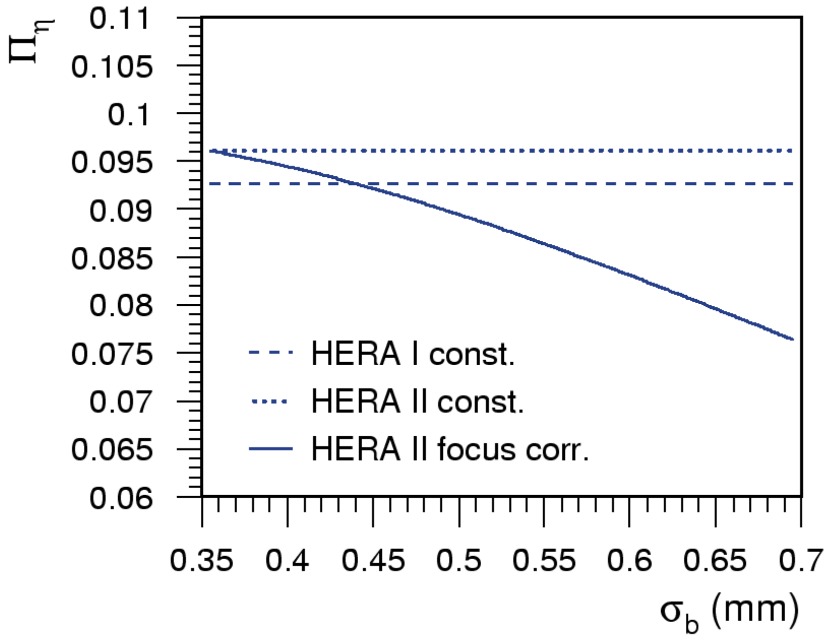
Transverse Polarimeter - Systematic Uncertainties

- Dominant contribution: analyzing power Π_η
  - Dependence on intrinsic beam width and divergence (focus)
  - Dependence on distance of Compton interaction to calorimeter (D_{IP})
  - Absolute scale
- Focus dependence included 2004 as correction to analyzing power, but not for IP distance
- Current contribution from IP distance is estimated as upper limit from geometrical acceptance
- The three contributions are correlated

  $\longrightarrow$ Need detailed realistic simulation of magnetic beam line (interaction vertex distribution)

  $\longrightarrow$ Need precise calorimeter response, i.e. $\eta(y)$-transformation and energy resolution for simulation

Source of systematic uncertainty	$\Delta P/P$
Electronic noise	$< \pm 0.1\,\%$
Calorimeter calibration	$< \pm 0.1\,\%$
Background subtraction	$< \pm 0.1\,\%$
Laser light polarisation	$\pm 0.1\,\%$
Compton beam centering	$\pm 0.4\,\%$
Focus correction	$\pm 1.0\,\%$
Interaction point region	$\pm 0.3\,\%$
Interaction point distance	$\pm 2.1\,\%$
Absolute analyzing power scale	$\pm 1.7\,\%$
Total systematic uncertainty	$\pm 2.9\,\%$

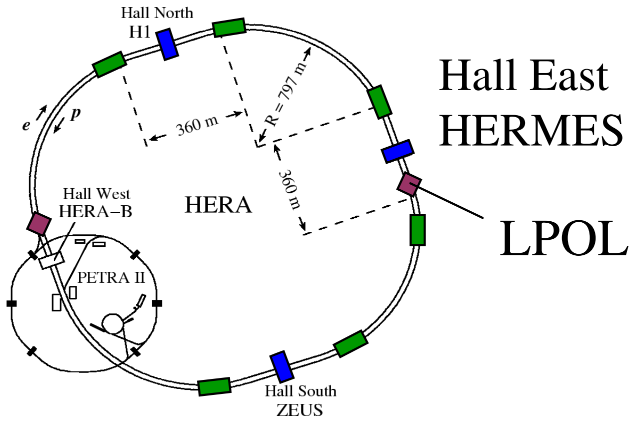


Systematics: [A+07b,CGOS04]

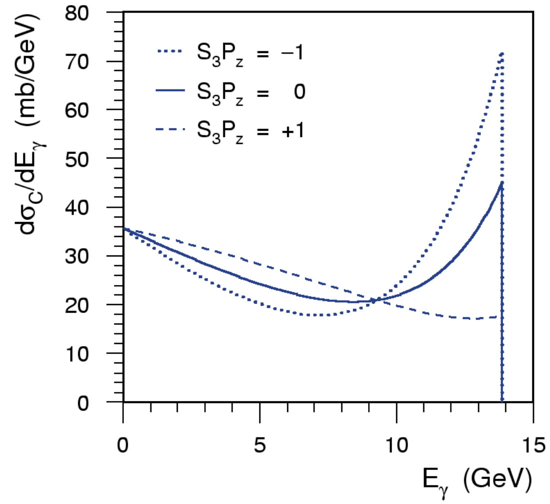
Longitudinal Polarimeter - Experimental Setup

- Measures longitudinal polarization in-between the HERMES spin rotators
- Operation 1997 - 2007
- Longitudinal polarization

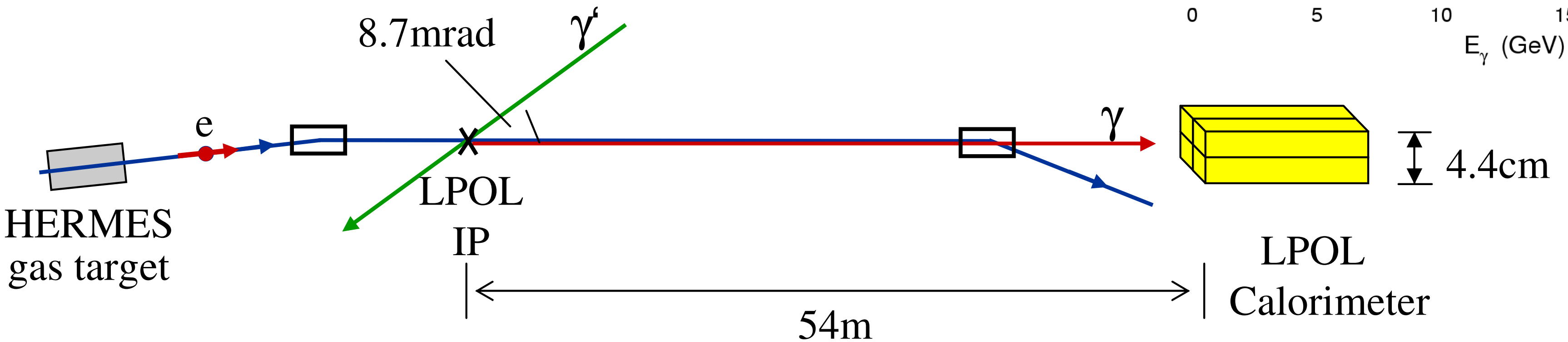
  → Energy dependent asymmetry between left and right laser helicity states



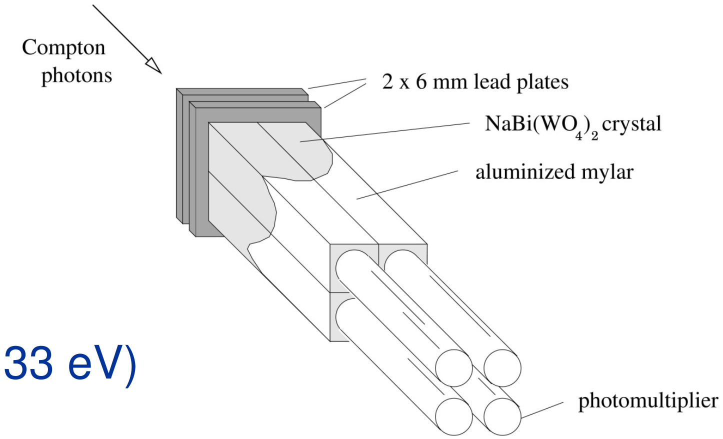
$$\mathcal{A}(E_\gamma) = \Delta S_3 P_z \frac{\Sigma_{2z}}{\Sigma_0}$$



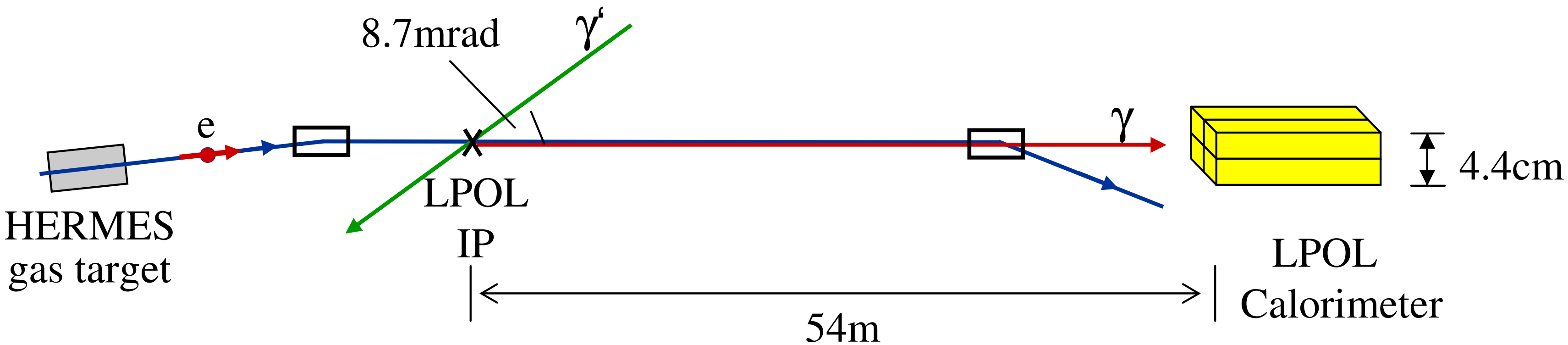
- Multi-photon Mode: $n_\gamma \approx 1000$ per bunch crossing
  - Bremsstrahlung's background from long straight section too high for single-photon mode



Longitudinal Polarimeter - Apparatus



- Compact electromagnetic Čerenkov calorimeter
  - 4 $NaBi(WO_4)_2$ crystals, ~19 X_0 deep, with 4 PMTs
  - Crystals optically isolated
    - → Energy sharing allows positioning to < 1 mm
- Laser
  - Frequency-doubled Nd:YAG laser: green 532 nm (2.33 eV)
  - Pulsed at 100 Hz, 3 ns long with 100 mJ per pulse
  - Synchronized with lepton bunches
  - Trigger for read-out at 200Hz, every 2nd event is background event
  - Circular polarization by Pockels cell, flipped every pulse
  - Monitored using Glan-Thompson prism
    - → Measured circular polarization $S_3 > 0.999$

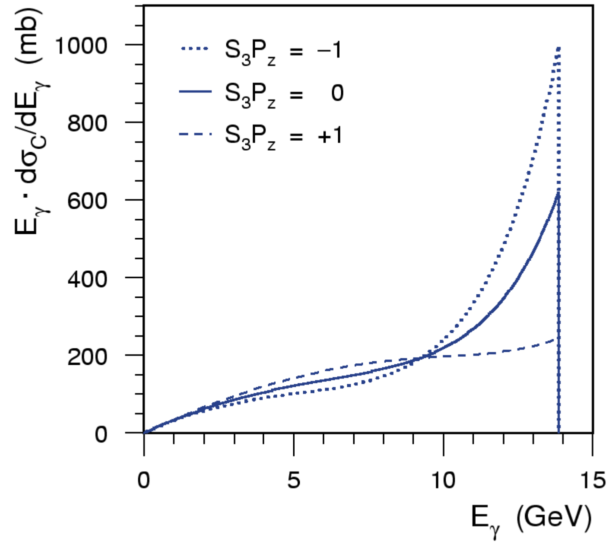


Longitudinal Polarimeter - Polarization Measurement

- Multi-photon mode: Detector signal corresponds to integral of energy-weighted cross-section

$$I_{S_3 P_z} := \int_{E_\gamma^{\min}}^{E_\gamma^{\max}} r(E_\gamma) E_\gamma \frac{d\sigma_C}{dE_\gamma} dE_\gamma$$

  - $r(E_\gamma)$ = single-photon relative response function, constant for linear detector
  - $E_\gamma^{\min}$ = energy threshold of detector

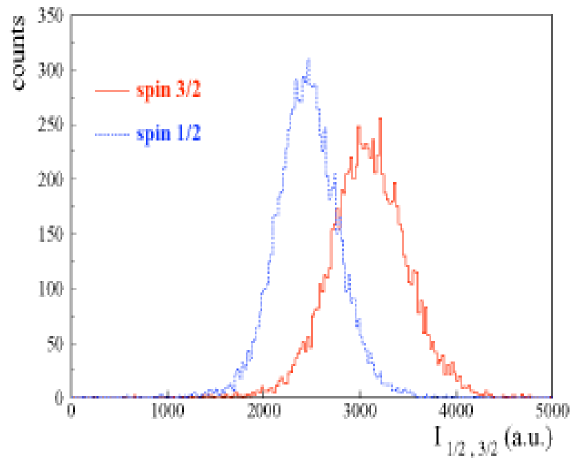


- Energy dependent asymmetry then becomes

$$\mathcal{A} := \frac{I_{S_3 P_z<0} - I_{S_3 P_z>0}}{I_{S_3 P_z<0} + I_{S_3 P_z>0}} = \Delta S_3 P_z \Pi_z$$

  - Analyzing power from test beam: $\Pi_z = 0.1929 \pm 0.0017$
  - Energy-weighted cross section distributions differ most at Compton edge

    $\longrightarrow$ Not strongly dependent on $E_\gamma^{\min}$



- Calorimeter response is critical issue

  $\longrightarrow$ Total energy in detector: $E > 5$ TeV !

- Statistical uncertainty $\delta P/P \approx$ 1-2% per minute
  - Single-bunches: $\delta P/P \approx$ 6% per 5 minutes

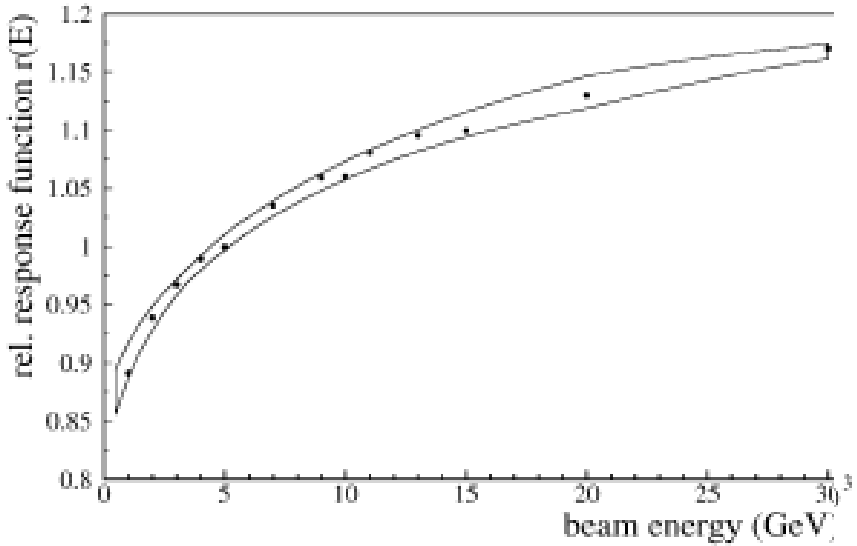
LPOL: [B+02a]

Longitudinal Polarimeter - Systematic Uncertainties

- Dominant uncertainty: analyzing power
  - Determined from test beam measurements
  - Cross-checked with data taken with a tungsten-scintillator sampling calorimeter
- Contributions to analyzing power
  - Shape of single-photon response function
    - $\longrightarrow$ Measured in test beams
  - Extrapolation single-photon to multi-photon mode
    - $\longrightarrow$ Measured in tunnel using a NDF to attenuate signal over 3 orders of magnitude
- Replacement of crystals in 2004
  - Performance cross-checked with sampling calorimeter, but not in test beams
    - $\longrightarrow$ Extra uncertainty as upper limit

$\longrightarrow$ Current best estimate $\frac{\Delta P}{P} = 2.0\%$

Source of systematic uncertainty	$\Delta P/P$
Analyzing power	$\pm 1.2\,\%$
Response function from test beam	$\pm 0.9\,\%$
Extrapolation single- to multi-photon	$\pm 0.8\,\%$
Analyzing power long-term stability	$\pm 0.5\,\%$
Gain matching	$\pm 0.3\,\%$
Laser light polarization	$\pm 0.2\,\%$
Helicity dependent luminosity	$\pm 0.4\,\%$
Interaction region stability	$\pm 0.8\,\%$
Total (HERA I)	$\pm 1.6\,\%$
Extra uncertainty for new calorimeter	$\leq \pm 1.2\,\%$
Total (HERA II)	$\pm 2.0\,\%$



LPOL Systematics: [B+02a, A+05, A+07b]

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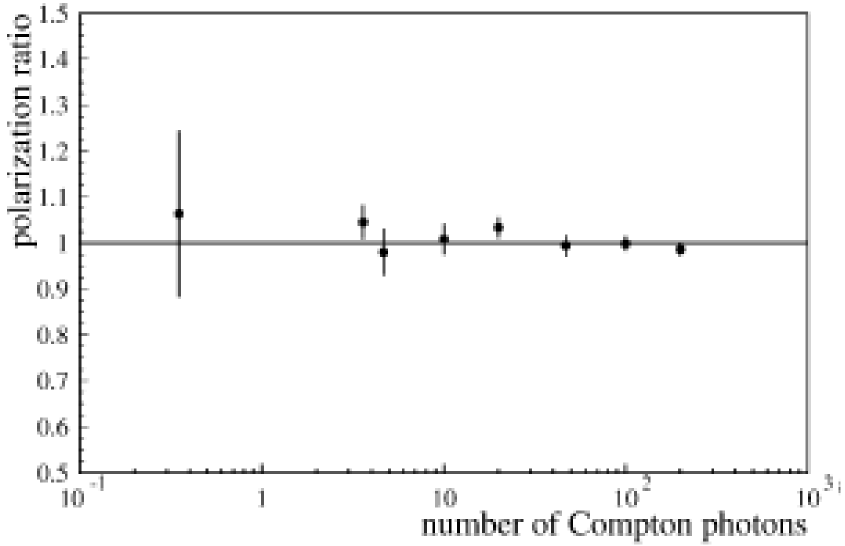


LPOL Systematics: [B+02a, A+05, A+07b]

Cavity Longitudinal Polarimeter - Motivation

- Why building a third polarimeter?
  - Both transverse and longitudinal polarimeter are statistically limited
    - TPOL needing scattering rate <100 kHz to maintain single-photon mode
    - LPOL being limited by laser pulse frequency of 100 Hz

    $\longrightarrow$ Statistical precision of groups of bunches on per minute level sufficient, but faster bunch-wise measurement desirable
  - Both polarimeters have systematical uncertainties around 2% or higher
    - Spatial asymmetries at TPOL are difficult to handle
    - Energy asymmetries at LPOL easier, but self-calibrating properties by using markers in the energy distribution of single or few photons are unavailable

    $\longrightarrow$ The combined results of H1 and ZEUS need a more precise polarization measurement in order not to be dominated by polarization
- Third polarimeter project employs a Fabry-Perot cavity to stock laser photons with a very high density at the Compton interaction point
  - Works in continuous few-photon mode: $n\gamma \approx 1$ per bunch crossing
    - Very high statistics with scattering rates in $\mathcal{O}$(MHz)
    - Self-calibrating properties: Use Compton and Bremsstrahlung's edges for calibration

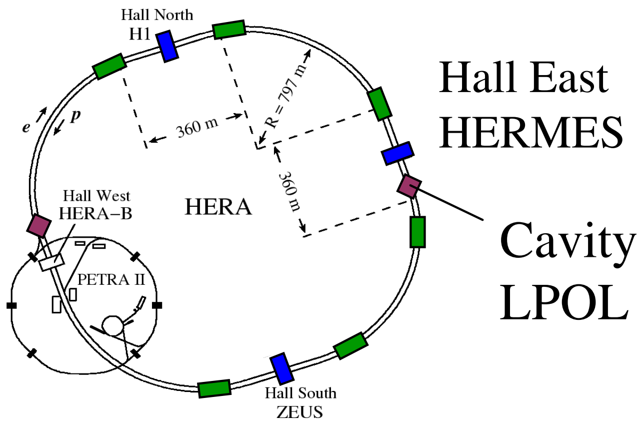
    $\longrightarrow$ Very fast measurement with small systematics

    $\longrightarrow$ Technically very challenging

Cavity LPOL: [Zha01, Zom03]

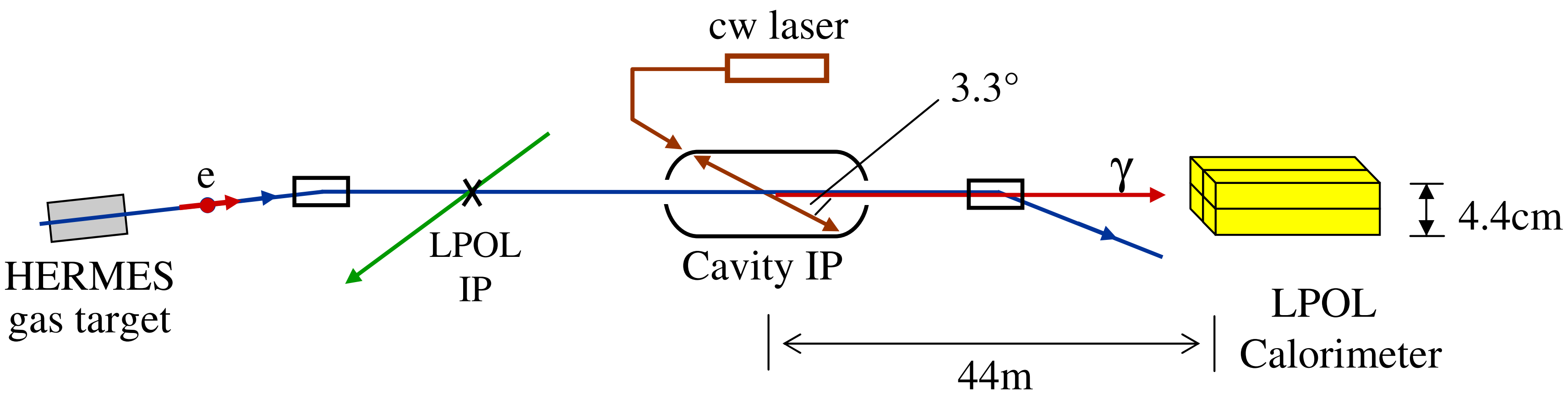
Cavity Longitudinal Polarimeter - Experimental Setup

- Measures longitudinal polarization in-between the HERMES spin rotators
  - Fabry-Perot cavity installed spring 2003
  - First Compton events observed in March 2005
  - Much increased operation till end of HERA
    - Over 450 hours of efficient data taken (Oct. 2006 – end)



- Continuous few-photon mode: $n\gamma \approx 1$ per bunch crossing

  $\longrightarrow$ Very high statistics, one measurement per bunch and helicity only ≈ 10 seconds

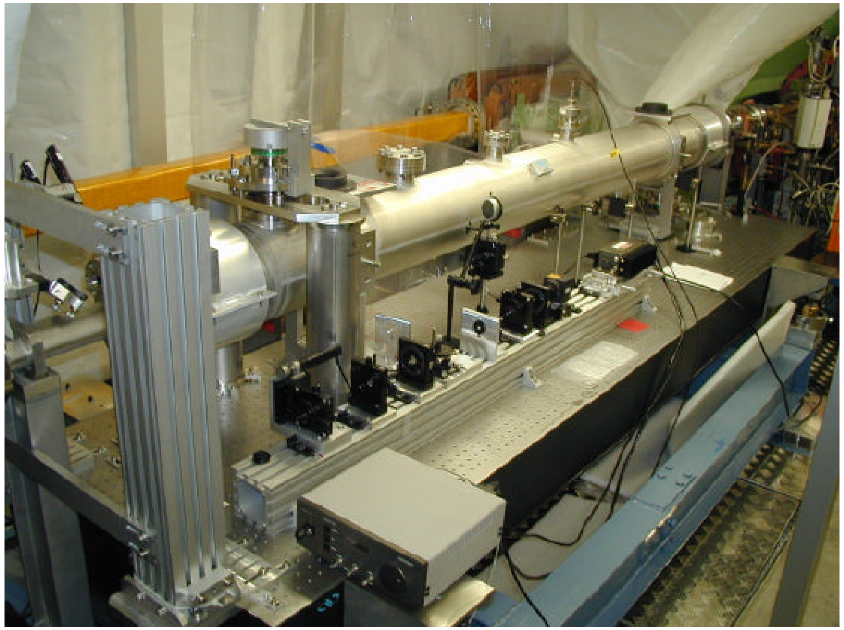


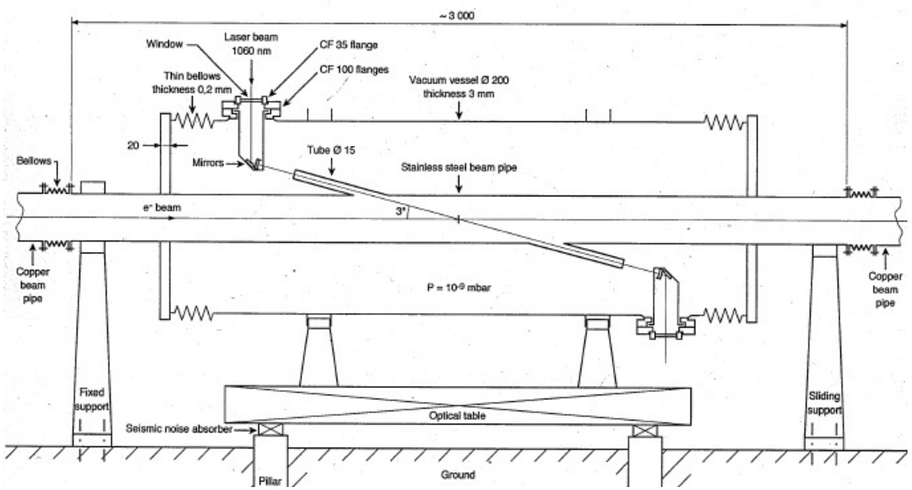
Cavity LPOL: [Zha01, Zom03]

Cavity Longitudinal Polarimeter - Apparatus

- Laser
  - Infrared Nd:YAG laser: 1064nm, initial power 0.7W, cw
  - Laser and all optical components on table in tunnel
  - Circular polarization by rotating quarter wave plate, flipped every few seconds
  - Monitored and measured behind cavity
- High finesse Fabry-Perot Cavity
  - Length 2 m, crossing angle 3.3°
  - Cavity mirrors inside vacuum vessel
  - Finesse ≈30000
  - Amplification of laser power by means of constructive interference, gain ≈5000

→ Laser power stored ≈3 kW

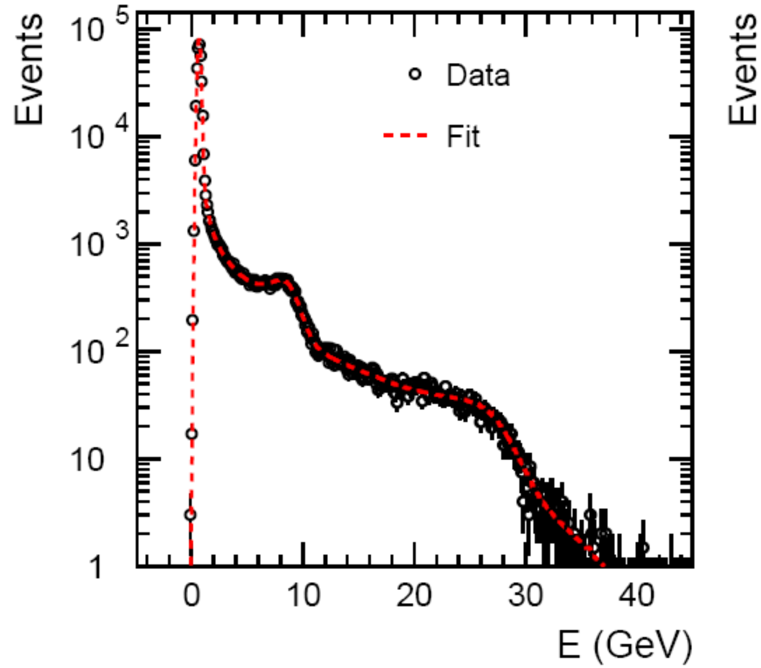


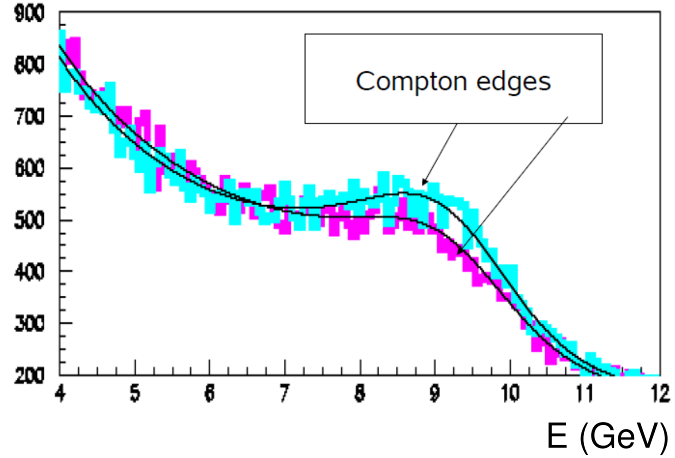


Cavity LPOL: [Zha01, Zom03]

Cavity Longitudinal Polarimeter - Polarization Measurement

- Measures longitudinal polarization by energy asymmetry from Compton cross section
- Overall fit to energy distributions for left and right laser helicity states
- Absolute calibration using Compton and Bremsstrahlung's edge positions
- Contributions included in description
  - Synchrotron radiation peak
  - Black body radiation
  - Compton peak, rate and flux
  - Bremsstrahlung's edge, rate and flux
  - Detector resolution + non-linearity parameters
- Detailed Monte Carlo simulation of the calorimeter response
  - E.g. description of the synchrotron radiation peak using MC input





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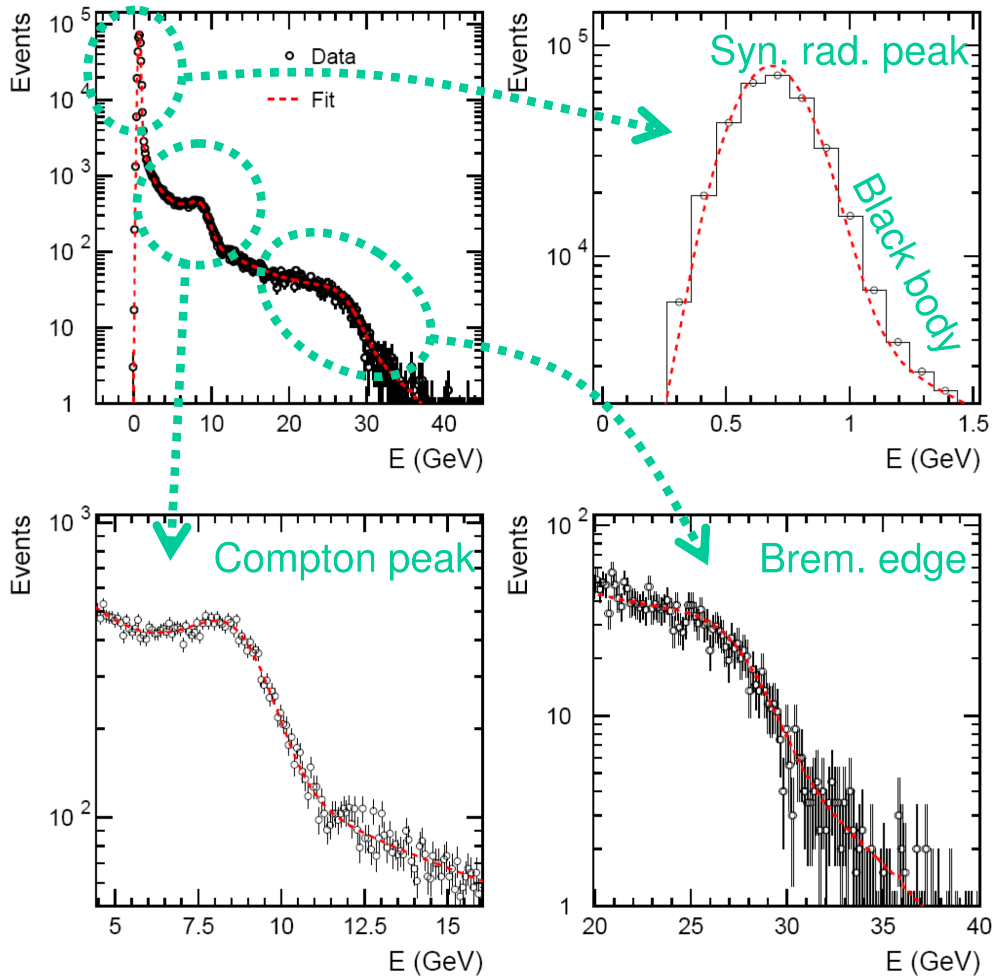


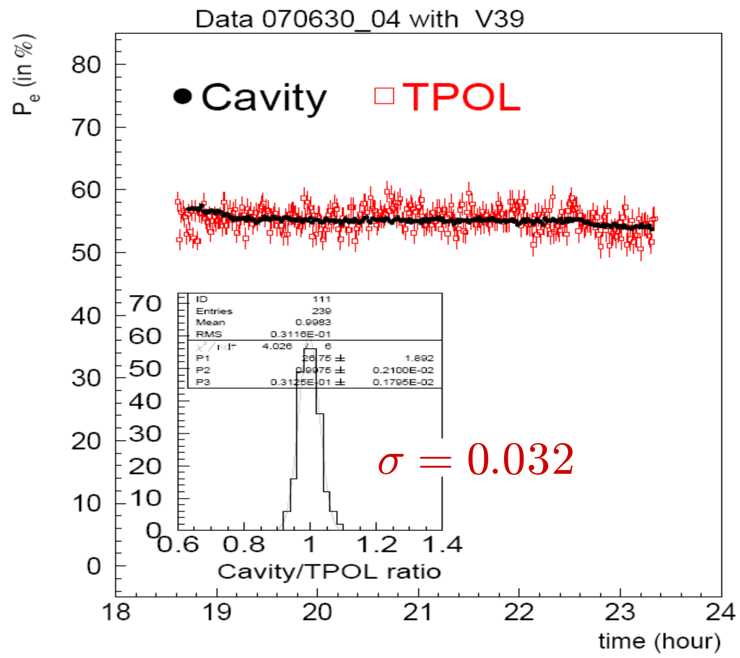
Cavity LPOL: [Zha01, Zom03]

Cavity Longitudinal Polarimeter - Systematic Studies

- Statistical uncertainties
  - $\delta P/P \approx 3\%$ per bunch and 10 s doublet

  → Much higher statistical precision than other two polarimeters
- Systematical studies include
  - Laser polarization uncertainty
  - Laser circularity (MOCO position scan)
  - Laser power variation
  - Electronic noise
  - Detector parameters
  - Calorimeter position scan in x and y
  - Synchrotron radiation cut
  - Black body temperature
  - Beam position scan
  - E-beam energy uncertainty
- Preliminary errors conservatively estimated
- Some studies have common uncertainty sources

  → Further error reduction expected with improvement of analysis



- Preliminary systematic uncertainties
  - From HERA: 0.70%
  - From laser: 0.75%
  - From detector: 0.1%

  → Total (absolute): $\delta P \sim 1\%$
- All data has been analyzed by now

→ Publication with final data analysis and errors being prepared and expected this year

Conclusion and Outlook

- Combined efficiency of TPOL and LPOL polarimeters
  - Around 99% over all years of HERA II running (2001-2007)
- Concurrent running of either TPOL and LPOL or TPOL and Cavity LPOL
  - As Cavity LPOL and LPOL shared the same detector location
- Polarization measurement with a high finesse Fabry-Perot cavity at HERA has been established
  - Successful operation of Cavity LPOL with increasing data taking frequency till the end of HERA

- All three polarimeters work on finalization of their systematic uncertainties
  - Current status:

$\frac{\Delta P}{P}$

TPOL	2.9%	} 3.4%
LPOL	2.0%	}
Cavity	1.4 - 2.5%	(@ P = 40-50%)

- Final polarization values and uncertainties expected this year

$\longrightarrow$ Combined systematic uncertainty is hoped to be reduced to at least <3%!

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