Lepton beam polarisation for
the HERA experiments ZEUS and H1

- Polarisation at collider machines
- The HERA storage ring
- The HERA polarimeters
- The collider experiments ZEUS and H1
- The HERA II upgrade
- Data taking in 2003
Polarisation at collider machines

Polarized beams are produced in several colliders world-wide, e.g.
- RHIC ($pp$ collisions)
- SLAC ($e^+e^-$, one beam polarized)
- LEP ($e^+e^-$, polarisation for beam diagnostics only)
- HERA ($ep$, $e$ beam polarized)

Techniques to obtain polarized beams
- $p$ beam and linear colliders: start with polarized source
- $p$ storage ring: avoid depolarizing resonances during acceleration
- $e$ storage ring:
  Sokolov-Ternov effect
  slow built-up of polarisation at full energy

Physics analyses:
- polarized $p$ → study origin of proton spin
- longitudinally polarized $e$ → electroweak physics
The Sokolov-Ternov effect

- Particle motion in storage ring: perpendicular to $B$-field of bending dipoles
- Spins are aligned parallel or antiparallel to the magnetic field

- Synchotron radiation may cause spin flip
- Probability for spin flip $p(\uparrow \rightarrow \downarrow)$ differs from $p(\downarrow \rightarrow \uparrow)$
The Sokolov-Ternov effect (cont’d)

Equilibrium: \[ N(\uparrow) \times p(\uparrow \to \downarrow) = N(\downarrow) \times p(\downarrow \to \uparrow) \]

\[ P = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} \]

Theory:
\[ P = P_{\text{max}} \times (1 - \exp(-\frac{t}{\tau})) \]
\[ P_{\text{max}} = \frac{8}{5\sqrt{3}} \approx 0.924 \]
\[ \tau \approx 100s \frac{(R/m)^3}{(E/\text{GeV})^3} \]

Real machine: depolarizing effects:
- non-uniform magnetic fields
- quadrupoles, etc
- \( \to \) smaller \( P_{\text{max}} \), smaller \( \tau \)

Slow built-up of transverse polarisation
\[ \tau(\text{LEP}) = \mathcal{O}(10h) \]
\[ \tau(\text{HERA}) = \mathcal{O}(30\text{min}) \]
Example: polarisation built-up at HERA

- Maximum polarisation $\approx 45\%$
- Rise-time $\approx 30$ min
- Polarisation tuning: optimize orbits and other machine parameters
- Constant monitoring by two independent polarimeters
The HERA storage ring

- HERA: $ep$ collider
- $E(e) = 27.6$ GeV
- $E(p) = 920$ GeV
- $E_{CM} = 320$ GeV
- $e$ beam polarized
- Collider experiments ZEUS, H1
- Fixed target exp. HERMES, HERA-b
- Integrated luminosity 120 pb$^{-1}$ per collider experiment (ZEUS, H1), mostly in $e^+p$ collisions
- Transverse $e$ beam polarisation about 60%
- Transverse $e$ polarisation: Not relevant for physics analyses
- Longitudinal $e$ polarisation for HERMES since 1994/95 (spin rotators)
  Left-handed or right-handed electrons $e_L, e_R$ for HERMES, not for H1, ZEUS
Spin rotators

- transv. pol.: spin aligned to $B$-field of bending dipoles
- long. pol.: well defined helicity $e_L$ or $e_R$
- Six dipole magnets
- Complex spin rotation and beam movement in 3D
- Beam direction after passing rotator is unchanged
The HERA upgrade (2000 – 2001)

- Add strong focusing magnets inside H1 and ZEUS
  - Increase specific luminosity
    - Synchrotron radiation sources close to interaction region, small aperture, beam steering “difficult”
- Remove compensating coils and add spin rotators
  - Longitudinal polarisation for H1 and ZEUS
    - Complex spin and beam orbit, delicate to tune
The HERA lepton ring

- two independent polarimeters
- TPOL measures transverse polarisation far from spin rotators \( P = P_y \)
- LPOL measures longitudinal polarisation between HERMES spin rotators \( P = P_z \)

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The HERA polarimeters

Compton scattering of high-energy electrons and LASER photons

- Electron and scattered photon beams are separated by bending magnets
- Detect scattered photons in a small calorimeter
- Cross-section is sensitive to beam polarisation
  \[ \sigma = \sigma_0(E) + P_x\sigma_x(E,\varphi) + P_y\sigma_y(E,\varphi) + P_z\sigma_z(E) \]

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The HERA LPOL setup

LASER beam crosses HERA lepton beam
analyze scattered Compton photons
using a small calorimeter

complicated LASER transport system

LPOL: measure energy asymmetry between left/right circular LASER light pulsed laser

TPOL: measure spatial asymmetry between left/right circular LASER light cw laser

Stefan Schmitt, University of Zürich

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LPOL cavity upgrade

- LASER with 0.7 W intensity is amplified in a Fabry-Perot cavity
  Increase probability of Compton scattering (1 per bunch-crossing)
  High precision polarimetry
- Similar cavity is operational at CEBAF
- HERA cavity commissioning ongoing
Typical HEP detectors: tracking, solenoid, calorimeter, muon chambers

Detectors are asymmetric

\((E_e = 27.5\, \text{GeV} \text{ and } E_p = 920\, \text{GeV})\)
Deep inelastic scattering

Neutral current

\[ e \rightarrow e' \]

\[ p \rightarrow q (\bar{q}) \]

\[ Z/\gamma \]

Charged current

\[ e \rightarrow \nu' \]

\[ p \rightarrow W^\pm \]

\[ q (\bar{q}) \]

Kinematic variables

momentum transfer \[ Q^2 = -(e - e')^2 \]

center-of-mass energy of \( eq \) system: \[ E_{eq} = \sqrt{s}, \hat{s} = sx \]

At high \( Q^2 \): observe unification of electroweak forces

With longitudinally polarized electrons: study helicity dependence
Neutral current cross-section:
\[ \sigma_{\text{NC}}^{\pm} \propto \frac{1}{Q^4} \frac{1}{x} \left[ Y_+ F_2^0(x, Q^2) + P \times (Y_+ F_2^P(x, Q^2) + Y_- x F_3^P(x, Q^2)) \right] \]

Structure functions:
- \( F_2^0 \) and \( x F_3^0 \)
- Polarized structure functions:
  - \( F_2^P \) and \( x F_3^P \)

\( e^+ p \) and \( e^- p \) data: measure \( F_2, x F_3 \)
+\( P \) and \(-P\): measure \( F_2^P, x F_3^P \)
Structure functions: HERA I and HERA II

HERA I:
\[
\approx 100 \text{ pb}^{-1} \text{ in } e^+p \text{ data}
\]
\[
\approx 16 \text{ pb}^{-1} \text{ in } e^-p \text{ data}
\]
per experiment \((P = 0)\)
→ measurement of \(xF_3\)

HERA II:
plan to have \(4 \times 250 \text{ pb}^{-1}\)
for each combination of \(e^\pm p\) and \(\pm P\)
→ measurement of \(F_2^P\) and \(F_3^P\)

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Measurement of the electroweak couplings

\[ F_{2}^{0,P}(x, Q^2) = \sum_{q} A_{q}^{0,P} x(q + \bar{q}) \]

\[ A_{q} = f \left( v_{q}, a_{q}, \frac{1}{Q^2 + M_{Z}^2} \right) \]

Simultaneous fit of \( v_{u}, a_{u}, v_{d}, a_{d} \)

Study for: \( 4 \times 250 \text{ pb}^{-1} \) of \( e^{\pm} p \) with \( P = \pm 0.7 \)

HERA measures light quarks

Complementary to

LEP measurements for heavy quarks
Charged current cross-section

\[ Q^2 = -q^2 \]

CC cross-section is a linear function of \( P \):

\[ \sigma^{e^-}_{\text{CC}} = \frac{1-P}{2} \sigma^L_{\text{CC}} + \frac{1+P}{2} \sigma^R_{\text{CC}} \]

Right-handed cross-section is zero in the SM

→ Look for new physics at \( P \) close to 1 (e.g. \( W_R \))

Need to know \( P \) with accuracy 1%

\[ \sigma(e^- p \rightarrow \nu X) \]

as a function of \( P \)

\[ Q^2 > 1000 \text{ GeV}^2 \]
$W$ mass measurement

HERA I:
Result from DIS2002 ($e^-p$)

$m_W = 79.9 \pm 2.2\text{(stat)}$
$\pm 0.9\text{(syst)} \pm 2.1\text{(pdf)} \text{GeV}$

HERA II:
High degree of polarisation
increase $\sigma(\text{CC})$, keep $\sigma(\text{bgr})$ constant

Accuracy for 1000 pb$^{-1}$
$\Delta m_W = 50 \text{MeV}$
(constrained fit, use $m_{\text{top}}$, etc)
Conclusions: HERA II data taking has started

- HERA operation restarted this autumn
- Background conditions improved for H1 and ZEUS
- HERA currents slowly increasing towards design values
- Polarized $e$ beam for H1 and ZEUS
  → electroweak physics, searches